THE STRESSES AROUND REINFORCED SQUARE OPENINGS WITH ROUNDED CORNERS IN A UNIFORMLY LOADED PLATE

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ABSTRACT

The stress field, expressed in stress concentration factors, around a reinforced square opening with rounded corners in a uniformly loaded plate was determined experimentally. The reinforcement represents a flat bar equal in thickness to that of the plating in which the opening was made. The effects of varying the corner radius and reinforcement height were investigated. In all cases the maximum stress occurs on the boundary of the opening, near the point of tangency of the corner radius with the side of the opening parallel to the uniformly applied load. The maximum stress concentration is plotted as a contour surface in Figure 23 against the ratio of the corner radius to width of opening, r/w, and the reinforcement height, expressed in multiples of plate thickness. Figures 21 and 22 are cross curves which define this contour.

ACKNOWLEDGEMENT

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CONTENTS

NOTATION

A	Cross-sectional area of plating
e_1, e_2	Principal strains
e_a, e_b	Strain in a- and b- directions, respectively
e_i	Strain in direction of loading at infinity
e_x, e_y	Strain in x- and y- directions, respectively
e'	Measured strain
E	Modulus of elasticity
k_a, k_b	Concentration factor in a- and b- direction, respectively
k_o	Concentration factor tangential to the boundary of the opening
k'	Concentration factor based on measured quantities
K	Transverse Sensitivity factor of gage
P	Applied load
r	Corner radius of square opening
S_1	A principal stress
S_a	Stress in the a- direction
t	Plate thickness
u	Poisson's ratio
w	Width of opening
(a,b)	Any orthogonal coordinate system
(x,y)	Orthogonal coordinate system, measured from center of opening. The x- axis is transverse to the direction of the applied load.
θ	Angular polar coordinate measured from the x-axis

I. INTRODUCTION

A. GENERAL

The purpose of this investigation was to determine, experimently, the elastic stress concentrations around a reinforced square opening with rounded corners in a uniformly loaded plate. This investigation was suggested by David Taylor Model Basin in connection with a broad program concerning the determination of the effects of internal discontinuities in structural members.

The immediate intent was to provide experimental verification of, or experimental information to aid in the development of, an analytical solution of the stress concentrations around reinforced square openings with rounded corners. A secondary intent was to provide, for the designer, an emperical solution to the stress concentrations for the given case.

B. BACKGROUND

In design work there arise circumstances under which it becomes necessary to cut an opening in a structural plate subject to a uniform stress. Such openings reduce the net cross sectional area available for carrying the stress producing load and produce a region of stress concentration. The choice of shape of the opening and the addition of reinforcement are means by which the designer attempts to restore to the member those characteristics which existed before the opening was made. In such cases, especially in the range of principal interest for ship structures, the designer has been

limited to his judgement or to openings having simple geometric shapes on which analytical studies could be made.

Around 1950 the Ship Structure Committee sponsored an investigation on reinforced cutouts in plates subject to uniform stress (1)*. This investigation was conducted by D. Vasarhelyi and R.A. Hechtman. The main effort was devoted to the region from the beginning of the plastic range to the ultimate strength of the plates. However, some information was obtained in the elastic region as reported in their first progress report (2). The appendix to this report contains a review of the references in technical literature on openings in plates, both mathematical analyses and experimental work.

In 1957 as part of the broad DTMB program concerning the determination of the effects of internal discontinuities in structural members, J.S. Brock did an "Analytical Determination of the Stresses Around Square Holes with Rounded Corners" without reinforcement (3). Effort is currently being made at DTMB towards an analytical solution of the problem investigated by the authors.

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* Numbers in parentheses refer to the Bibliography.

II. SCOPE OF THE EXPERIMENTAL INVESTIGATION

In order to fulfill the purpose of the investigation it was planned to obtain for the specimens shown in Figure 1 values of change in strain at selected locations versus change in applied tensile load. The model used in the investigation was to represent the case of a reinforced opening in a ship structure. As such the model was to be of sufficient thickness so that the reinforcement could be arc-welded to the plate by standard shipyard methods. The reinforcement was to represent the practice of reinforcing small openings with flat bar of a thickness comparable to that of the plating in which the opening was made.

Quarter inch plate was considered as being of sufficient thickness to be representative of ship structure plating and still be of a reasonable weight to be used for the model. In accordance with the preceeding paragraph the reinforcement was quarter inch flat bar so orientated as to have the same cross-sectional area on each side of the plate. The height of the reinforcement equals the width of the reinforcing flat bar. The initial height was arbitrarily set at eleven times the thickness of the plate, that being estimated as being sufficient to include the range of practical interest. This height was reduced by symmetrically milling the reinforcement so that the reinforcement height for each test would represent a flat bar whose width is an integral multiple of the plate thickness. By varying the reinforcement in this way the

reinforcement finally was reduced to a height of one times the plate thickness which is the condition of an opening in a plate without reinforcement. As it was known that the corner radius has an effect on the stress pattern and concentration value, some variation of radius was called for. Reference (3) being available, the choice of corner radius was based on that work.

Frost, Pihl, and Colvin concluded in reference (4) that for a plate subject to a uniaxial stress with a ratio of width of plating to width of opening of 5 to 1 or more, the stress values would be independent of the width of plating. Timoshenko in reference (5) arrived at a similiar conclusion. This ratio was used as the minimum allowable ratio between the width of the plating to the width of the opening in designing the specimen.

III. TESTS AND TEST METHOD

A. PRELIMINARY

To realize the purpose of this investigation it became desirable to have as large a model as possible consistent with the existing equipment and facilities. Suffice to say, several months of planning, designing and construction were required before the first test could be conducted. The following equipment was constructed:

1) Special two point coupling devices to couple the specimen to the testing machine.

2) A foundation and jig arrangement for milling the reinforcement between test.

3) Handling equipment.

B. DETAILS OF SPECIMENS

The specimens were fabricated at David Taylor Model Basin. The medium steel plating for all the specimens was from the same heat of steel, with flat bar being used for the reinforcement. The steel plate and flat bar were used in the as-rolled condition. The tensile properties of the steel were determined by a eight inch gage length ASTM standard flat tensile specimen cut from specimen #2. The modulus of elasticity (Young's Modulus) in tension was found to be 29.96 $\times 10^6$ lb. per sq. in. The actual magnitudes of the tensile properties have no effect on the results thus the results of this investigation can be applied to other types of material.

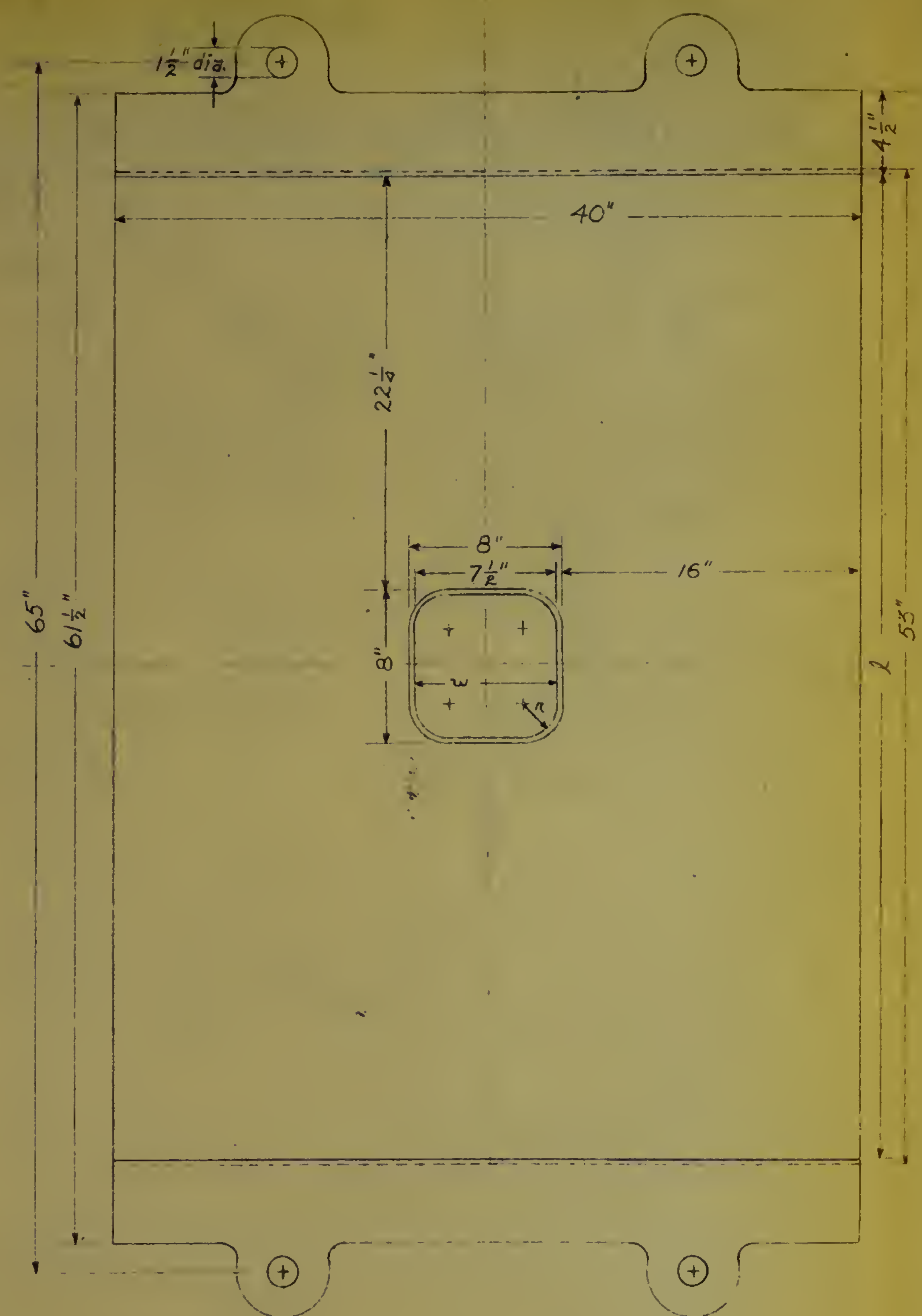
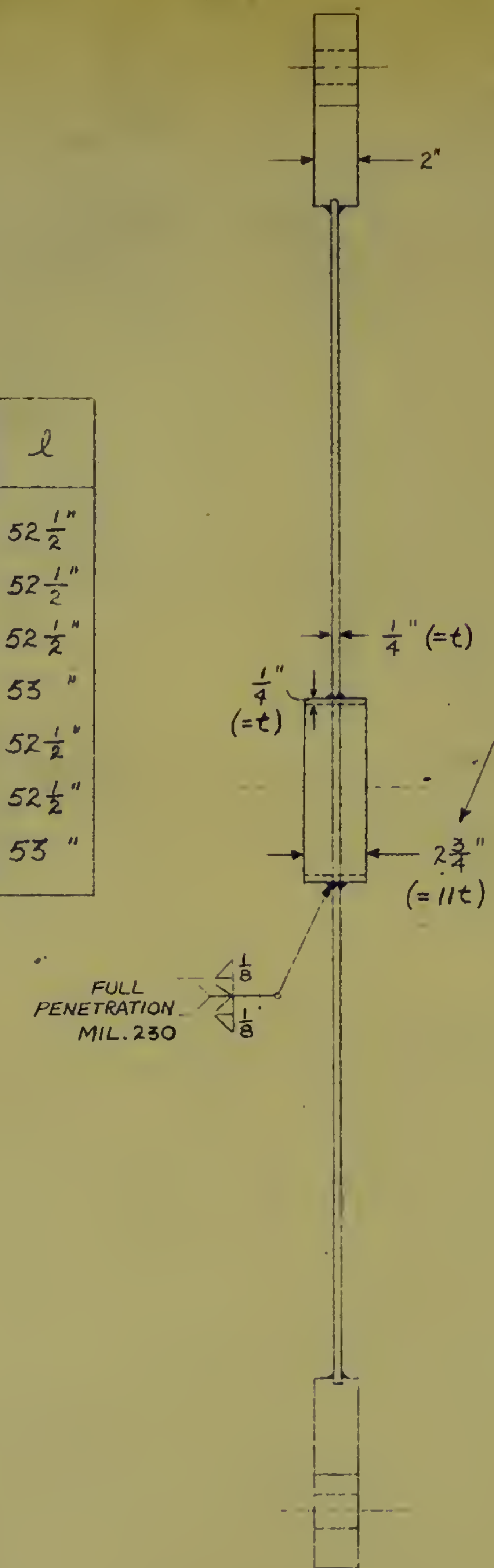


PLATE NO.	r/w	l
1	$\frac{1}{16}$	52½"
2	$\frac{1}{8}$	52½"
3	$\frac{3}{16}$	52½"
4	$\frac{1}{4}$	53"
5	$\frac{3}{8}$	52½"
6	$\frac{1}{2}$	52½"
7	NO OPENING	53"



NOTE:
THIS DIMENSION REDUCED SYMMETRICALLY BETWEEN EACH TEST BY MILLING ¼" FROM EACH SIDE GIVING REINFORCEMENT HEIGHTS OF 11t, 9t, 7t, 5t, 3t, AND 1t (NO REINFORCEMENT CONDITION).

DETAILS OF SPECIMEN

FIGURE 1

Figure 1 shows the "as designed" specimens. Included in Appendix VI are the dimensions lifted from the fabricated specimens. The details of welding are as shown.

Welding was in accordance with Military Specification MilSpec 230 with 100% penetration. Welding of the reinforcement was done on a welding flat. Single pass, step welding was employed with only the necessary restraint to hold the members being welded in alignment. With no other special precautions being observed it is understandable that warpage occurred. The means of fabrication were to represent shipyard practice and so no effort such as heat treatment was made to correct this warpage. The welding of the specimen strongbacks to the specimens tended to alleviate this condition. The specimen was welded to the strongbacks by inserting them into the alignment groove and using a fillet weld on each face of the specimen. Specimens were not tested until two months after fabrication and at least seven days after welding of the specimen strongbacks.

C. METHOD OF TESTING

The plates were tested in a 200,000 pound capacity universal hydraulic testing machine. Figures 2 and 3 show the test set-up. The specimen strongback was connected to the testing machine by the two point coupling system shown in Figures 4 to 6. The use of this method of coupling to the testing machine was to maximize the test length of the specimen. The testing machine had available 72 inches between

Figure 2 - Specimen #1 ready for test in the testing machine.

Figure 3 - The authors conducting test of specimen #4.

Figure 4 - Upper coupling crosshead and clevises coupling the specimen to the machine crosshead.

Figure 5 - Lower coupling crosshead made up.

Figure 6 - Coupling system nomenclature.

1. Specimen
2. Specimen strongback
3. Pin
4. Clevis
5. Stud
6. Coupling crosshead
7. Nut
8. Testing machine crosshead

the machine crossheads. To use as much of the available distance for a test length, the two point coupling system was designed to couple the specimen to the testing machine clear of this available distance and to obtain a uniform stress distribution as close to the points of load application as possible. It was necessary to align the specimen with the coupling system in order to produce a uniform tensile stress. By using a plumb, the upper and lower specimen strongbacks were aligned in the same plane. To achieve a symmetrical load distribution, readings were obtained on SR-4 strain gages placed near the clevises and the required adjustments made in the tension of the clevises.

As stated under the scope of the investigation the value to be measured was change in strain versus change in applied load within the elastic region. This measurement was independent of the procedure of loading and in conducting the tests two methods of loading procedure were used.

> Method 1. The testing machine load was varied at constant rate between the limits of the load. On each cycle of loading, the strain readings for a new gage location were obtained at designated loads.
>
> Method 2. While holding the machine load at desired levels, strain readings for all gages were taken.

Since in Method 1, contact resistance was a constant, the

slopes of the strain load curves were independent of that quantity. Method 2 was used when it was desirable to obtain the total strain at each gage location under the action of the loading. This latter method was used as a check method when it became necessary to approach the yield point or, as in some cases, to actually have local yielding in order to obtain a satisfactory load range.

D. GAGING AND MEASUREMENTS

SR-4 resistance wire strain gages were used to measure strains. To determine the degree of bending some gage locations had strain gages mounted on both faces of the specimen. The location of the strain gages on the different plates is given in Appendix VI. Temperature compensating gages were used.

Specimen #4 had an area coated with Stresscoat for the purpose of more clearly defining the strain patterns. Although repeated success was had on the Stresscoat test bar with the brittle lacquers, all attempts to obtain patterns on the plates under test failed. It is the opinion of the authors that this failure was largely due to the relatively small strains encountered within the testing range.

IV. RESULTS

A. INTRODUCTION AND DEFINITION OF TERMS

In order to properly interpret the results of this investigation, those terms which have an important influence on the results are included here.

In the design or analysis of a structural member in which a discontinuity produces a non-uniform stress distribution, the numerical value of the stresses only have meaning in evaluating the load-carrying ability of the particular member for a particular load. Thus, to better describe the effects of a square opening with rounded corners reinforced by a flat bar equal in thickness to that of the plate, the results presented herein will be presented as a comparison of the stresses with the applied uniform stress. This will be given in terms of stress concentration factors.

The STRESS CONCENTRATION FACTOR along the boundary of the opening at any point is the ratio of the stress at that point to the uniaxial stress applied at infinity, i.e. the uniform stress which would exist if no opening were present.

The STRESS CONCENTRATION FACTOR in the plate proper at any point is the ratio of the "virtual" stress at that point to the uniaxial stress applied at infinity.

It must be assumed that the proportional limit is not exceeded in interpreting these results. The stress concentration factor, as defined here, has no meaning once the proportional limit is passed. If a value indicates a stress in

excess of the proportional limit, the interpretation of what happens depends upon the characteristic of the material above this limit. For a ductile material, as the yield point is passed the total strain continues to increase but the stress remains constant as the additional load is carried by the adjoining material raising the average stress of the region, whereas a brittle material might fail, depending on the relative values of its ultimate strength and its yield strength. In either case neither the stress nor the strain will continue to vary above the proportional limit in the manner predicted by elastic theory.

The term <u>"VIRTUAL" STRESS</u> is borrowed from Hovgaard (6). The strains are those actually measured and for reasons of simplicity, which introduces only a small error for the conditions existing in the investigation, the product Ee is considered as a fictitious stress which will be referred to as the "virtual" stress.

The <u>STRAIN CONCENTRATION FACTORS</u> are the same as the stress concentration factors within the limitations pointed out above. Actually the results reported herein were determined from strain measurements, and the stress concentration factors determined from the strain concentration factors on the assumption that Saint Venant's maximum strain theory of elastic failure is a reasonable approximation for the purposes of this investigation.

Although the terms <u>SPECIMEN</u> and <u>PLATE</u> are used somewhat

interchangeably it is the intention of the term "plate" to refer to the specimen when it has the specimen strongbacks welded to it. The PLAIN PLATE refers to the specimen without an opening. The square opening has degenerated to the CIRCULAR OPENING CASE when the ratio of the corner radius to width of opening, r/w, equals one-half.

B. RESULTS

The results of the testing of the plain plate and the six plates with reinforced square openings with rounded corners are presented in Figures 7 to 23 with a summary of original data in Appendix VI. The uniform stress distribution produced in the plates by the loading system is demonstrated in Figure 7 which displays the results of testing the plain plate. Figure 7 also illustrates the coordinate axes and the method of measuring the angle θ for use in the succeeding curves.

Figures 8 to 13 show how the stress distribution along the boundary of the opening varies with a change in corner radius to width of opening ratio, r/w, for the various reinforcement heights. These curves show all the experimental points. Figure 14 to 19 are the same curves plotted as families for each r/w ratio. Figure 20 presents a typical example of distribution in the plate proper.

From a design standpoint Figures 21 to 23 are the most important. These are curves of the maximum stress concentration, occurring anywhere in the specimen, produced by the insertion of a reinforced square opening with rounded corners

into a specimen subject to a uniform axial stress.* Figure 23 is the contour surface of the maximum stress concentration plotted against r/w ratio and reinforcement height. Figures 21 and 22 are the cross-curve plots of the maximum stress concentration which define the contour surface of Figure 23.

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* In all cases, this maximum concentration was found to occur on the boundary of the opening.

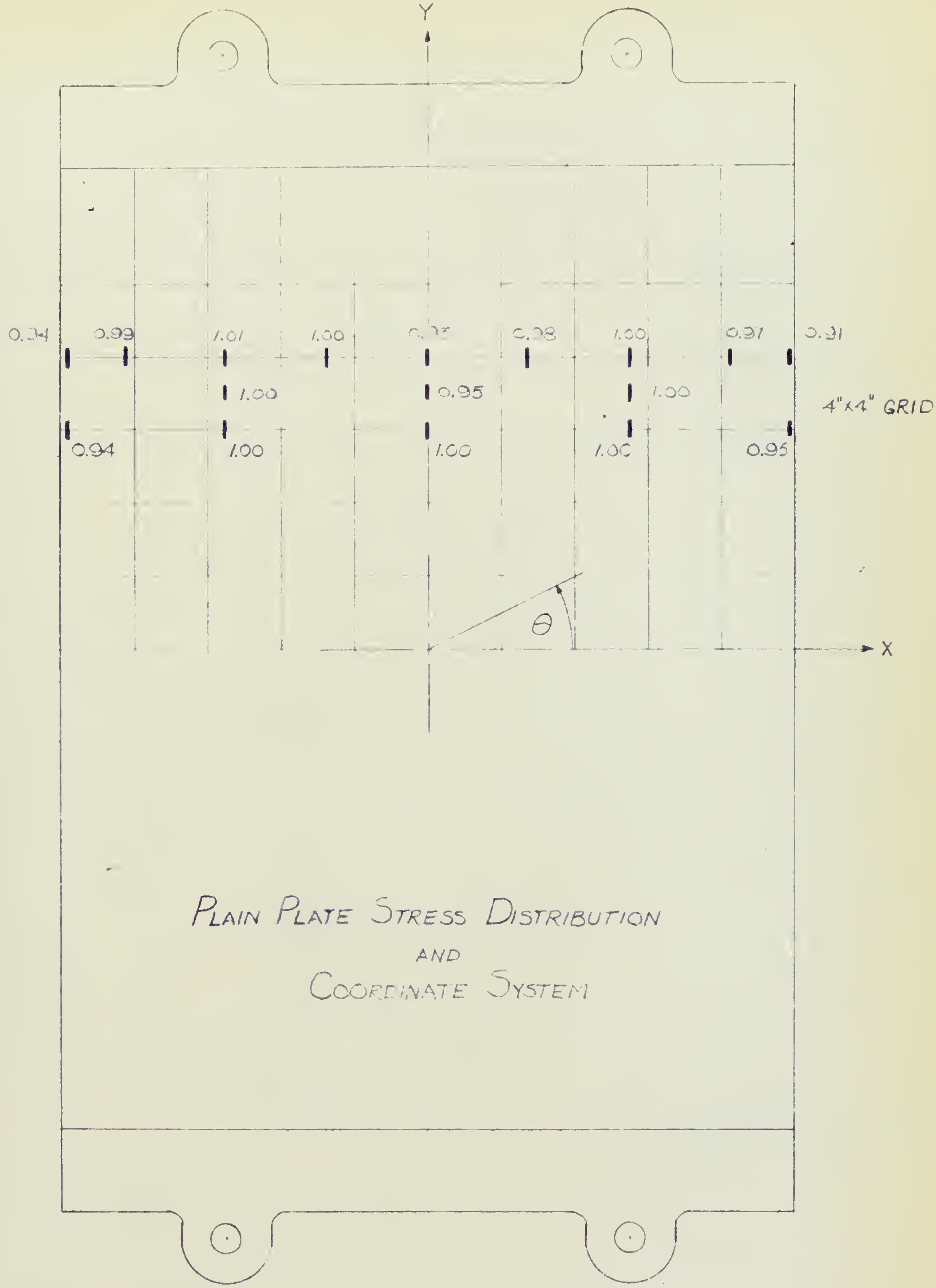
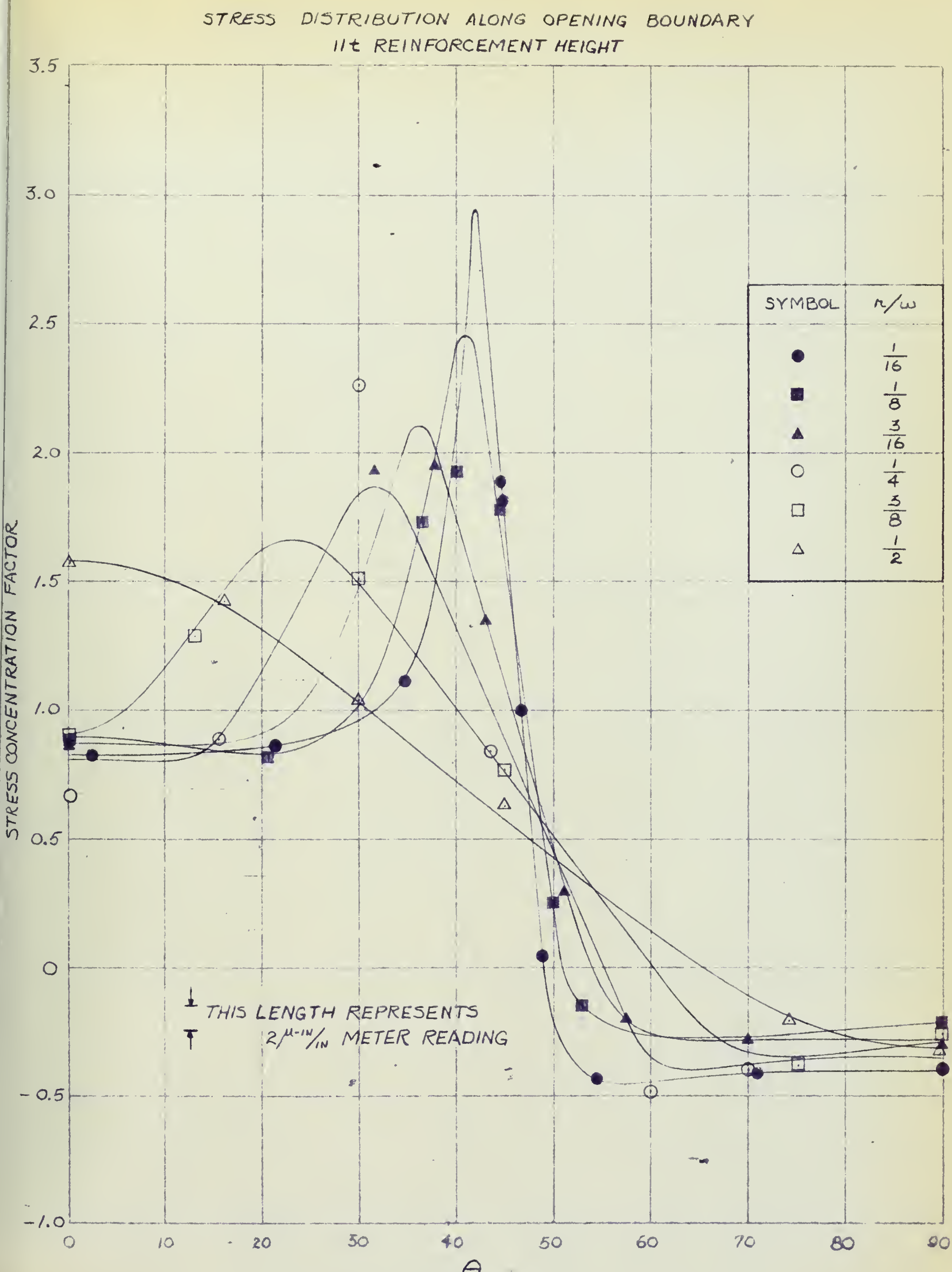


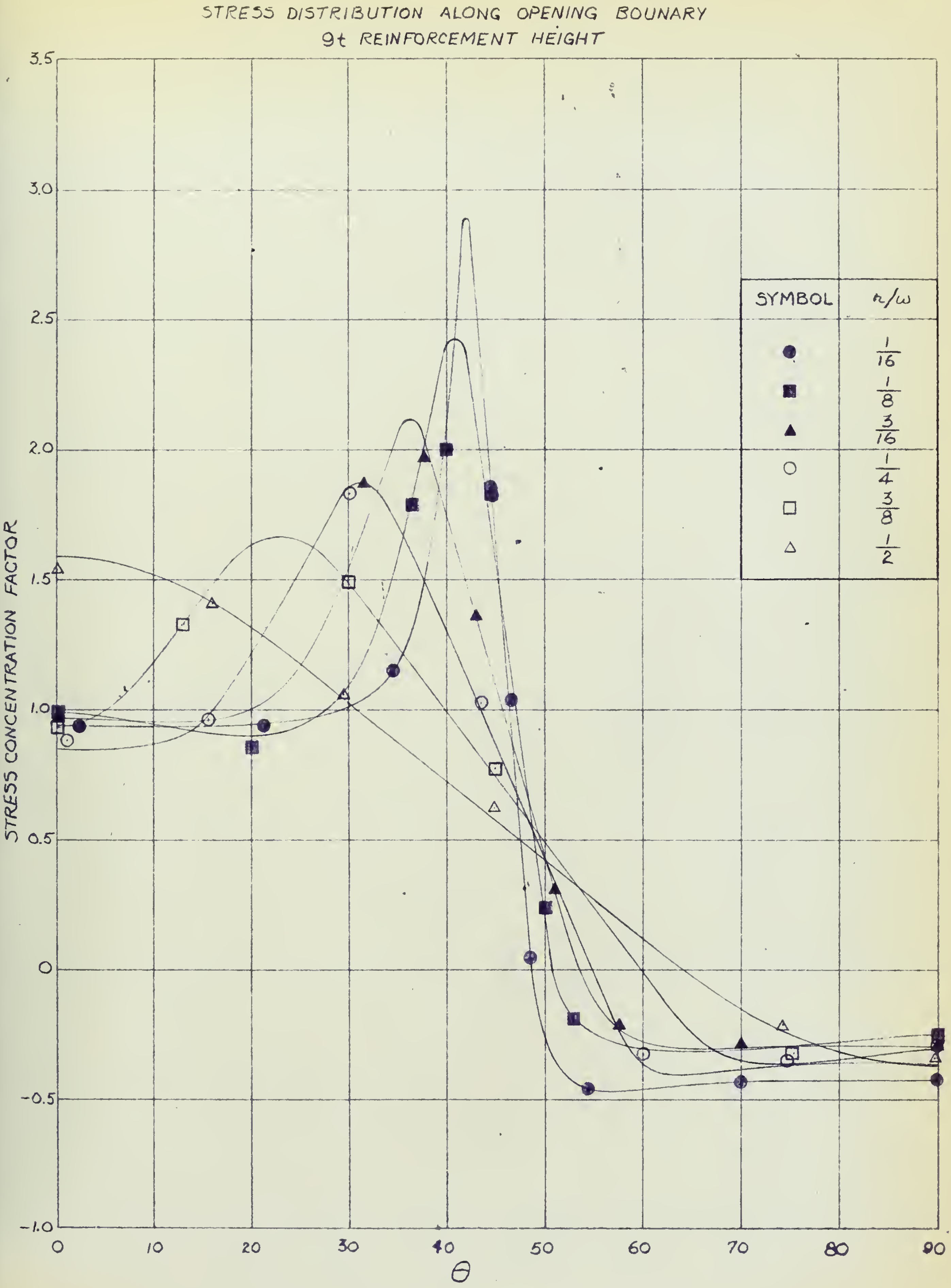
FIGURE 7

STRESS CONCENTRATION FACTORS SHOWING DISTRIBUTION OBTAINED BY USING TWO-POINT LOADING SYSTEM



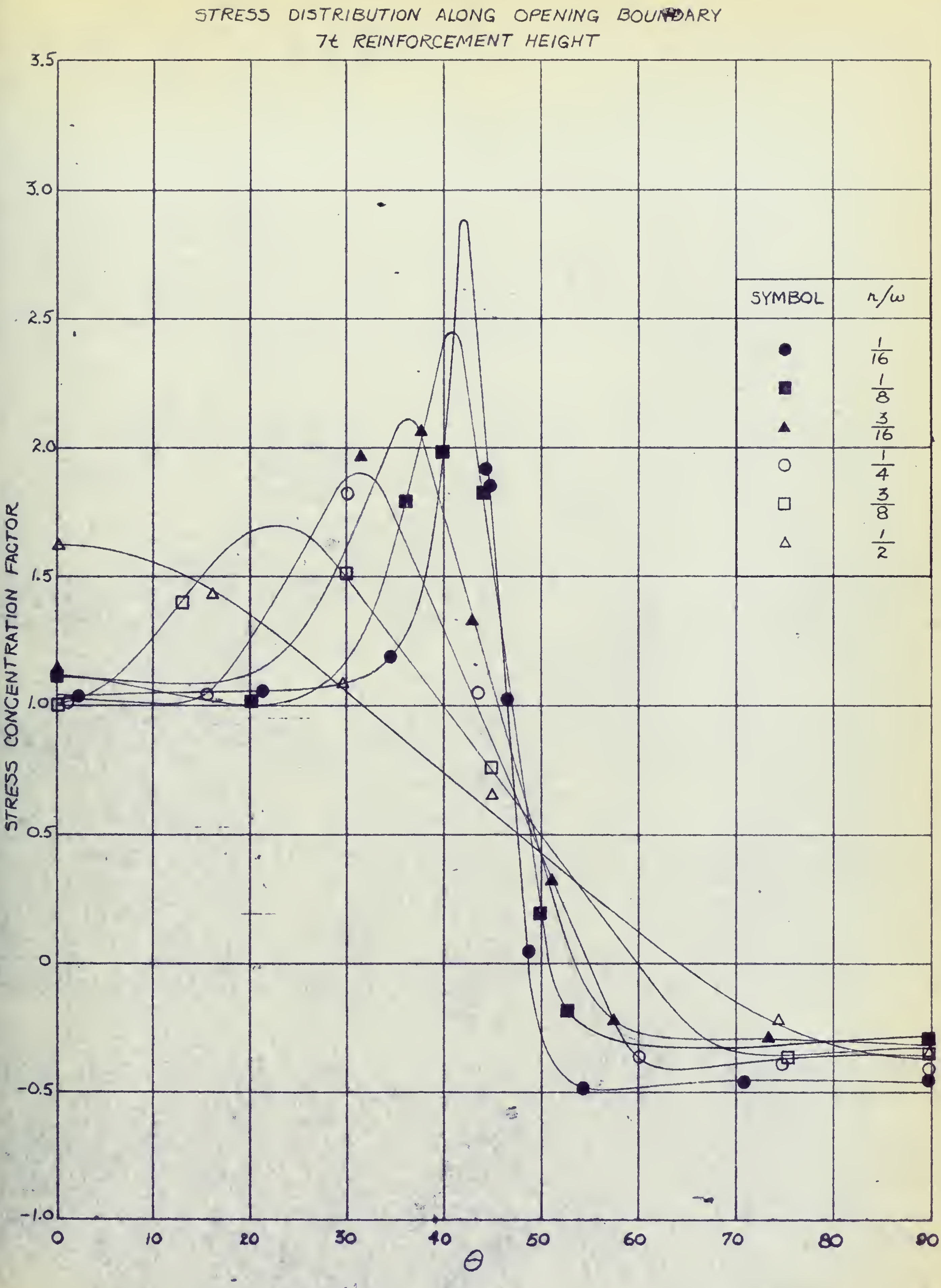
STRESS DISTRIBUTION ALONG OPENING BOUNDARY
11t REINFORCEMENT HEIGHT
STRESS CONCENTRATION FACTOR
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
-0.5
-1.0
0
10
20
30
40
50
60
70
80
90
θ
SYMBOL
r/ω
1/16
1/8
3/16
1/4
3/8
1/2
THIS LENGTH REPRESENTS
2 μ-in/in METER READING

FIGURE 8



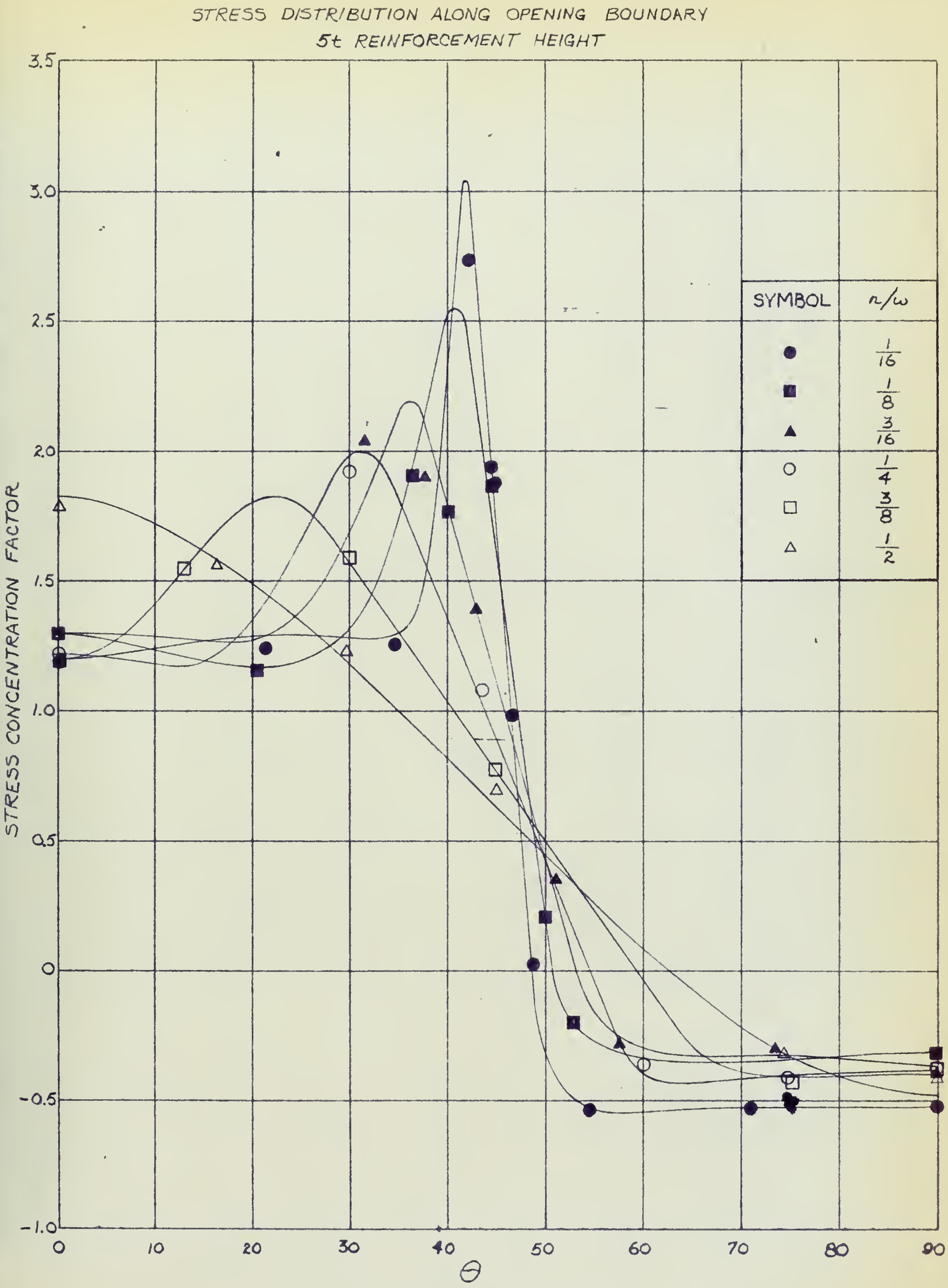
STRESS DISTRIBUTION ALONG OPENING BOUNARY
9t REINFORCEMENT HEIGHT
STRESS CONCENTRATION FACTOR
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
-0.5
-1.0
0
10
20
30
40
50
60
70
80
90
θ
SYMBOL
r/ω
1/16
1/8
3/16
1/4
3/8
1/2

FIGURE 9



STRESS DISTRIBUTION ALONG OPENING BOUNDARY
7t REINFORCEMENT HEIGHT
STRESS CONCENTRATION FACTOR
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
-0.5
-1.0
0
10
20
30
40
50
60
70
80
90
θ
SYMBOL
r/ω
1/16
1/8
3/16
1/4
3/8
1/2

FIGURE 10



STRESS DISTRIBUTION ALONG OPENING BOUNDARY
5t REINFORCEMENT HEIGHT
STRESS CONCENTRATION FACTOR
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
-0.5
-1.0
0
10
20
30
40
50
60
70
80
90
θ
SYMBOL
r/w
1/16
1/8
3/16
1/4
3/8
1/2

FIGURE 11

STRESS DISTRIBUTION ALONG OPENING BOUNDARY
3t REINFORCEMENT HEIGHT

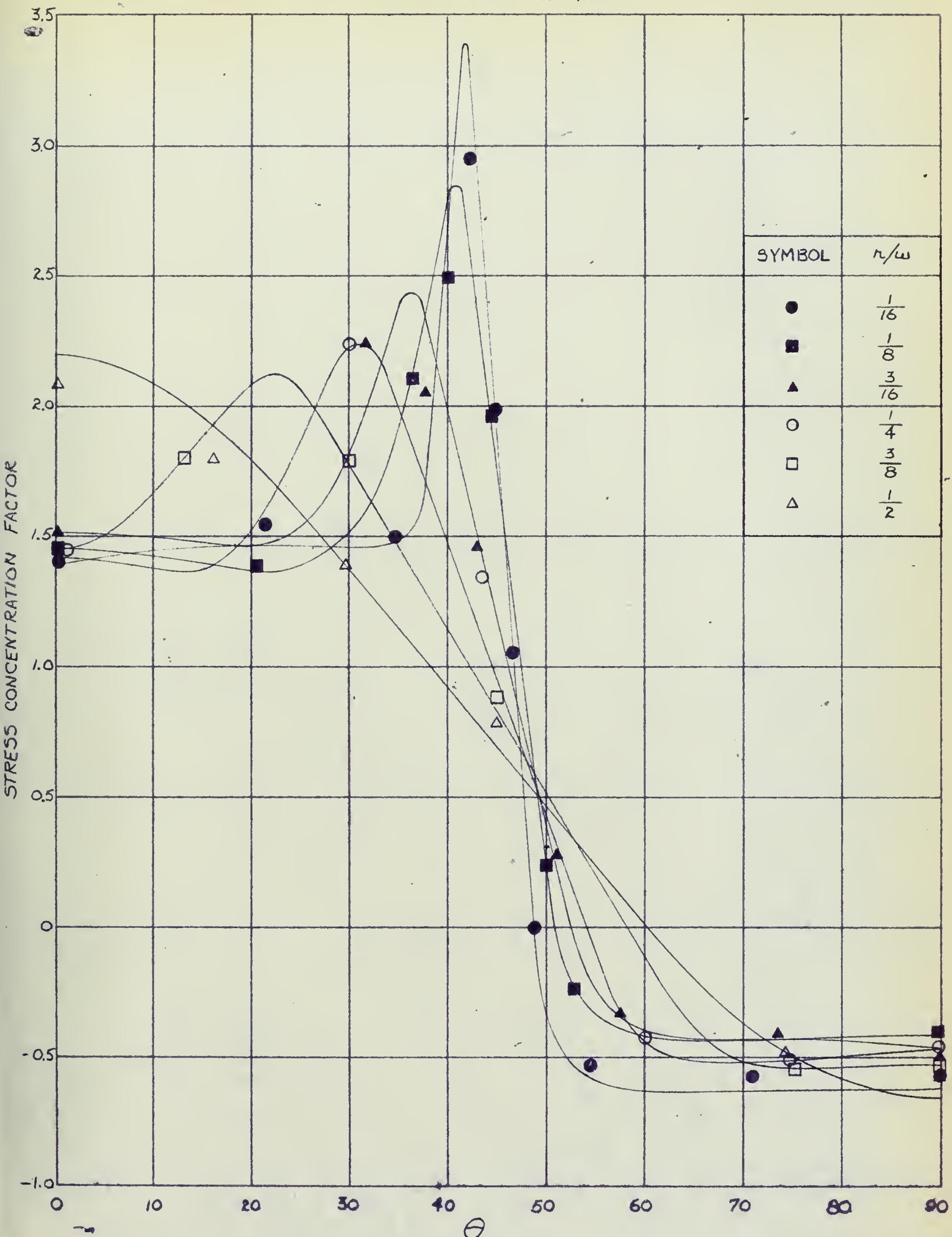


FIGURE 12

STRESS DISTRIBUTION ALONG OPENING BOUNDARY
1t REINFORCEMENT HEIGHT

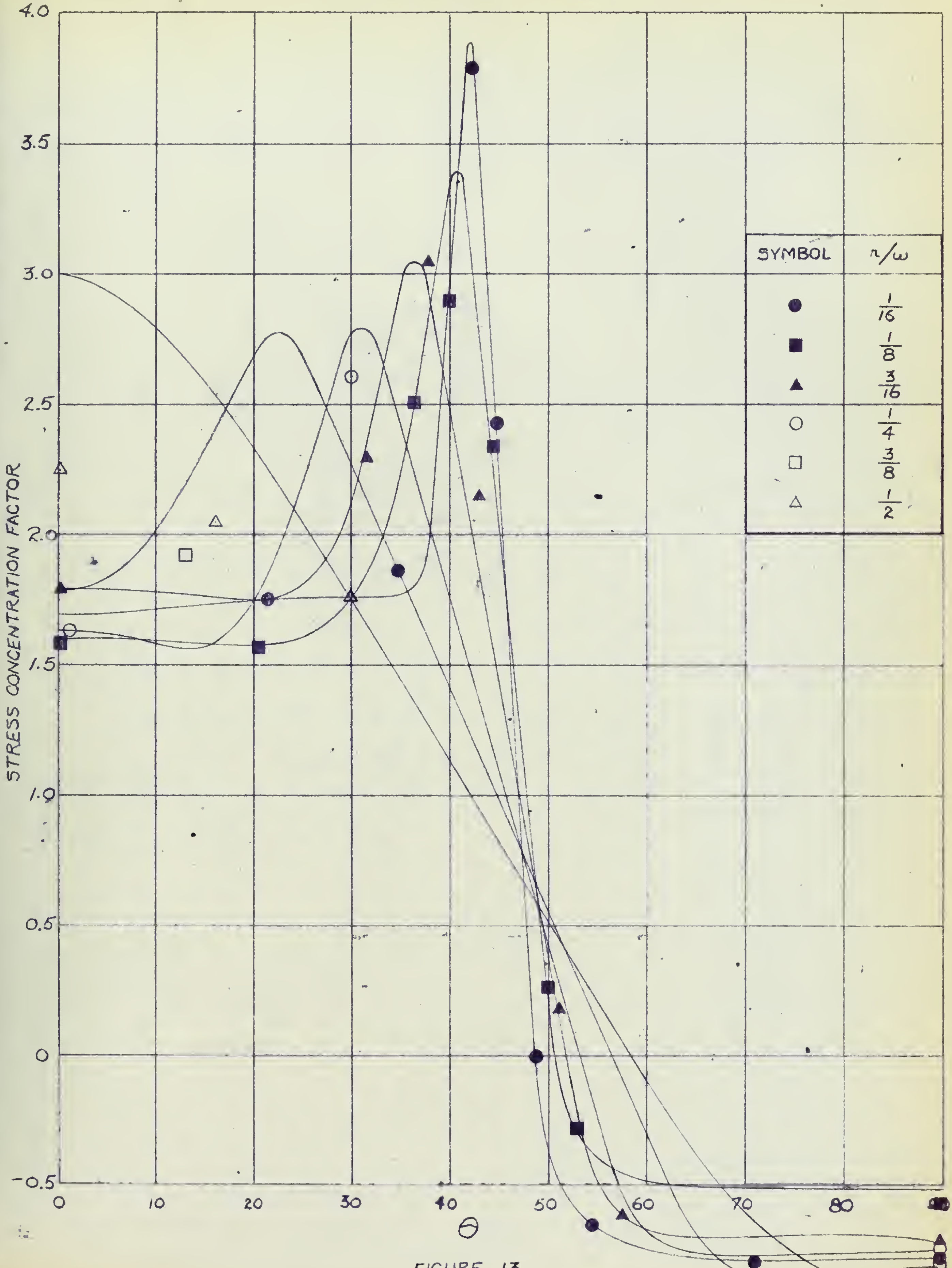


FIGURE 13

STRESS DISTRIBUTION ALONG OPENING BOUNDARY

$r/\omega = \frac{1}{16}$

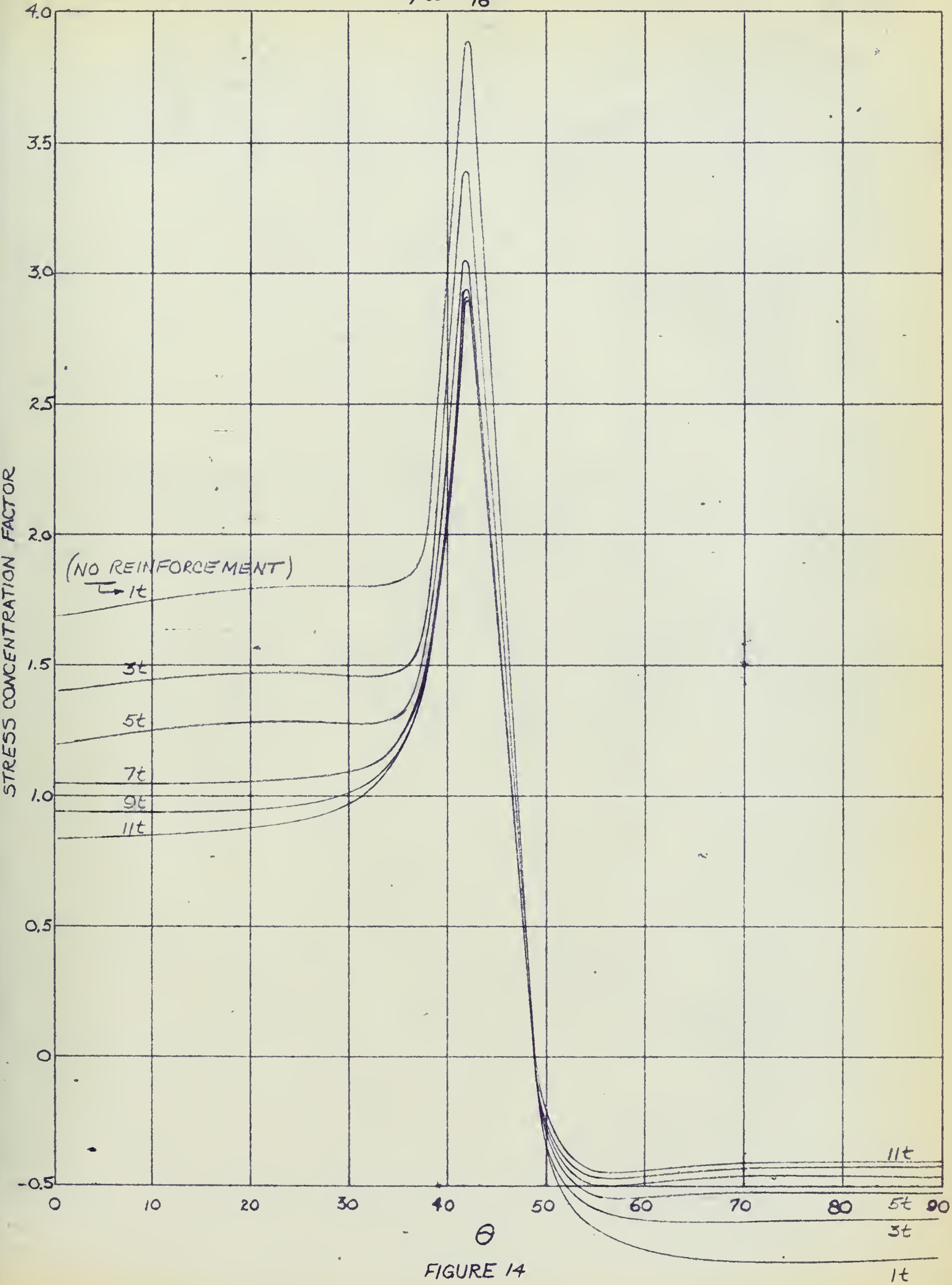


FIGURE 14

STRESS DISTRIBUTION ALONG OPENING BOUNDARY

$r/w = \frac{1}{8}$

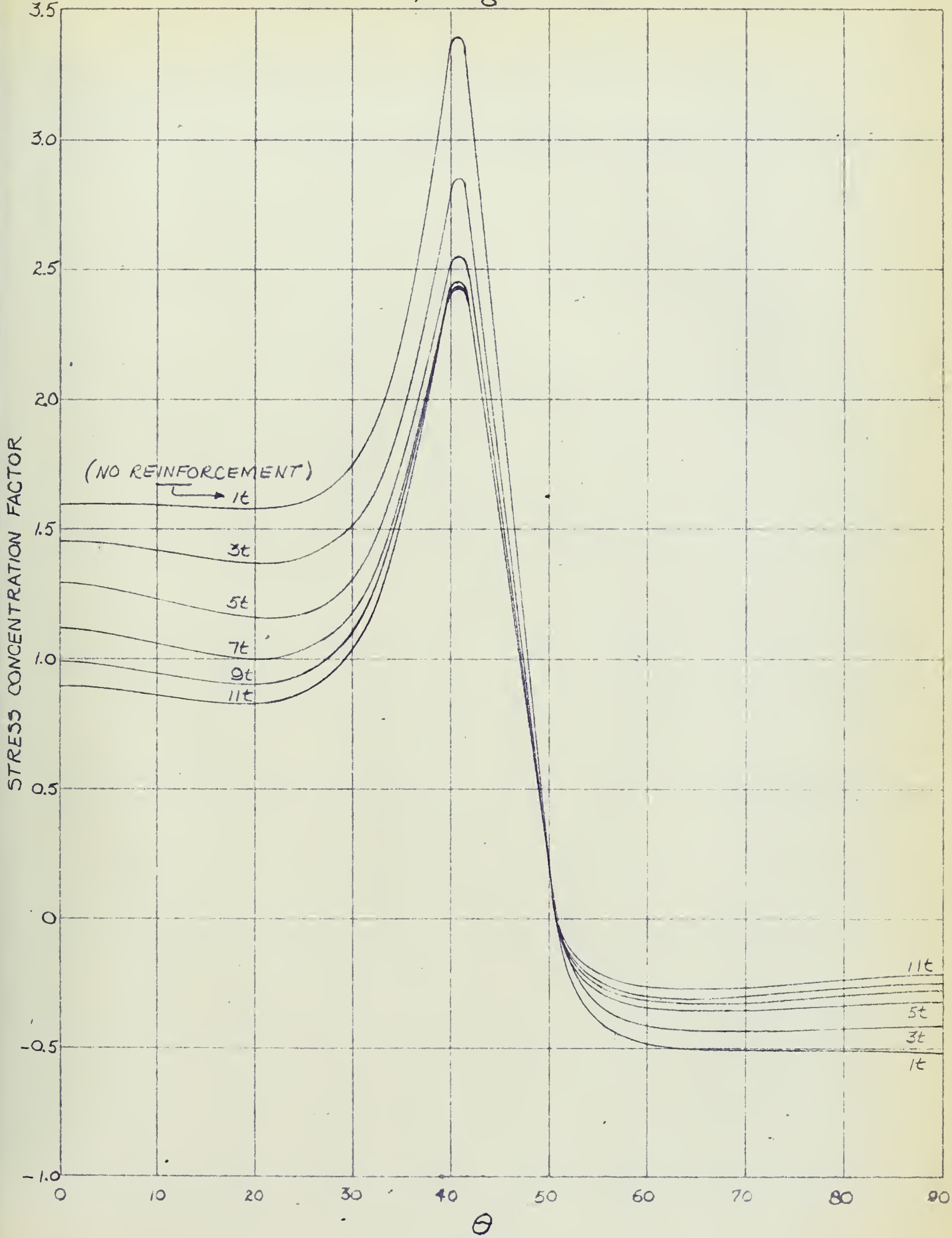


FIGURE 15

STRESS DISTRIBUTION ALONG OPENING BOUNDARY

$r/w = \frac{3}{16}$

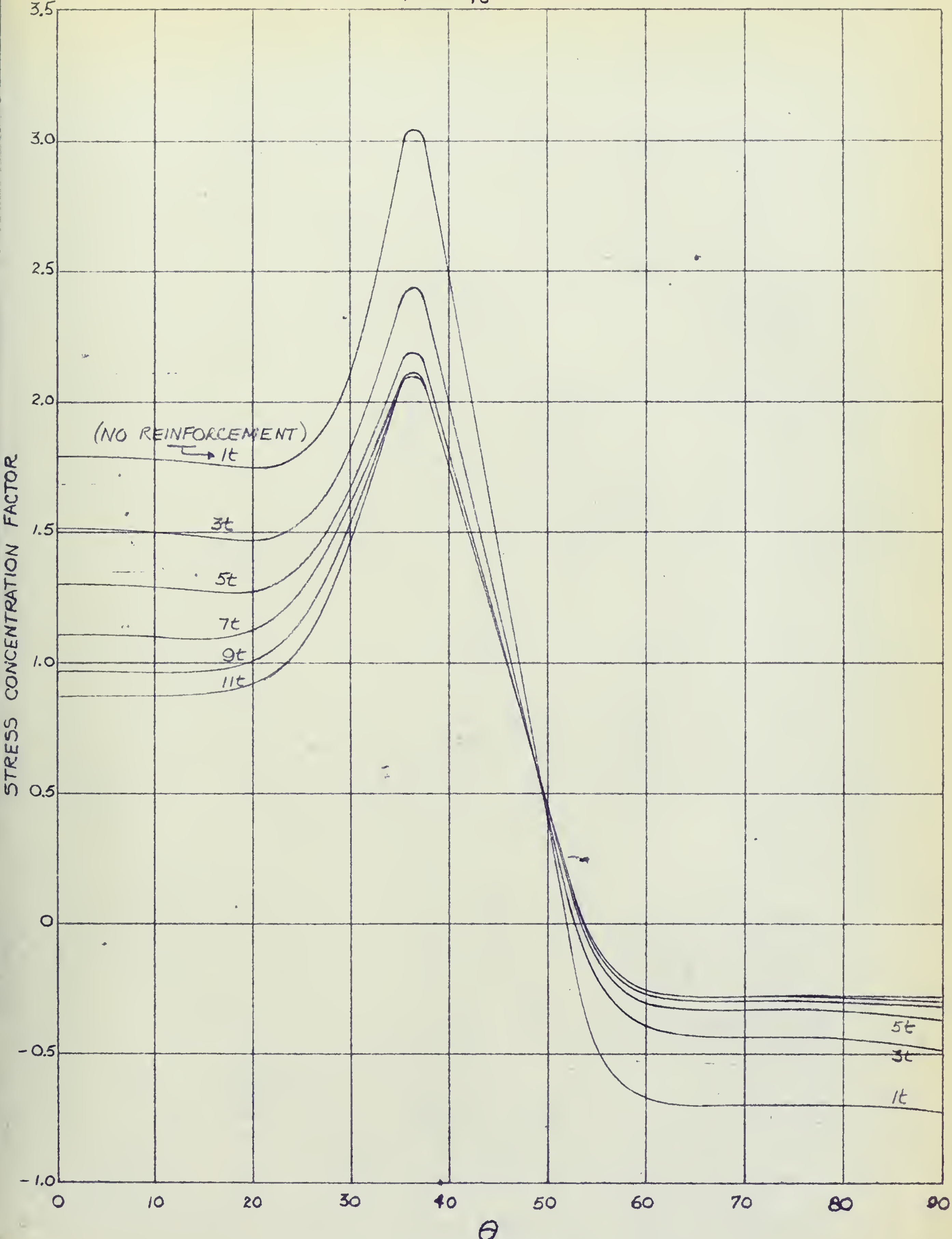


FIGURE 16

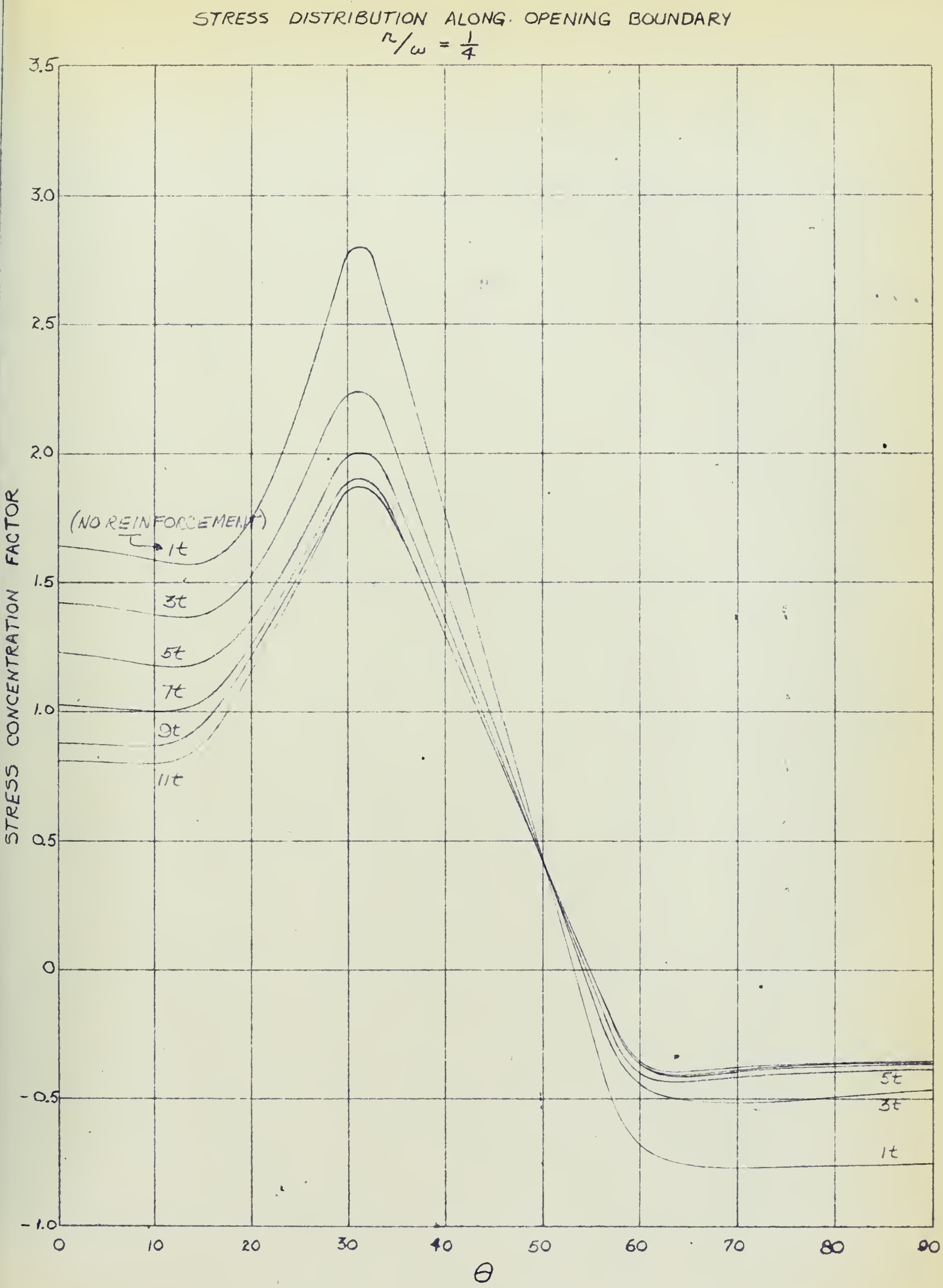

STRESS DISTRIBUTION ALONG OPENING BOUNDARY
r/ω = 1/4
STRESS CONCENTRATION FACTOR
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
-0.5
-1.0
0
10
20
30
40
50
60
70
80
90
θ
(NO REINFORCEMENT)
1t
3t
5t
7t
9t
11t
5t
3t
1t

FIGURE 17

STRESS DISTRIBUTION ALONG OPENING BOUNDARY

$r/\omega = \frac{3}{8}$

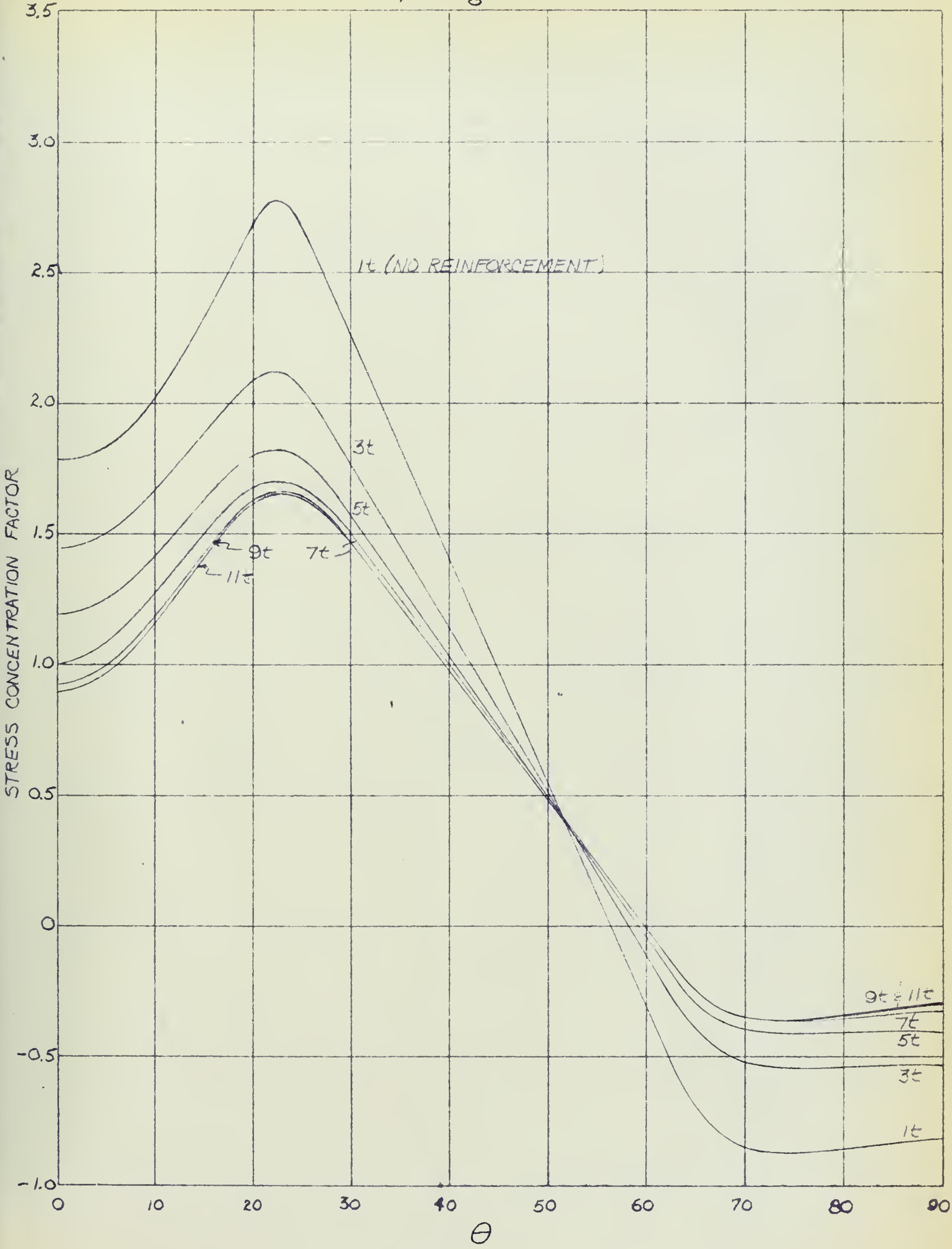
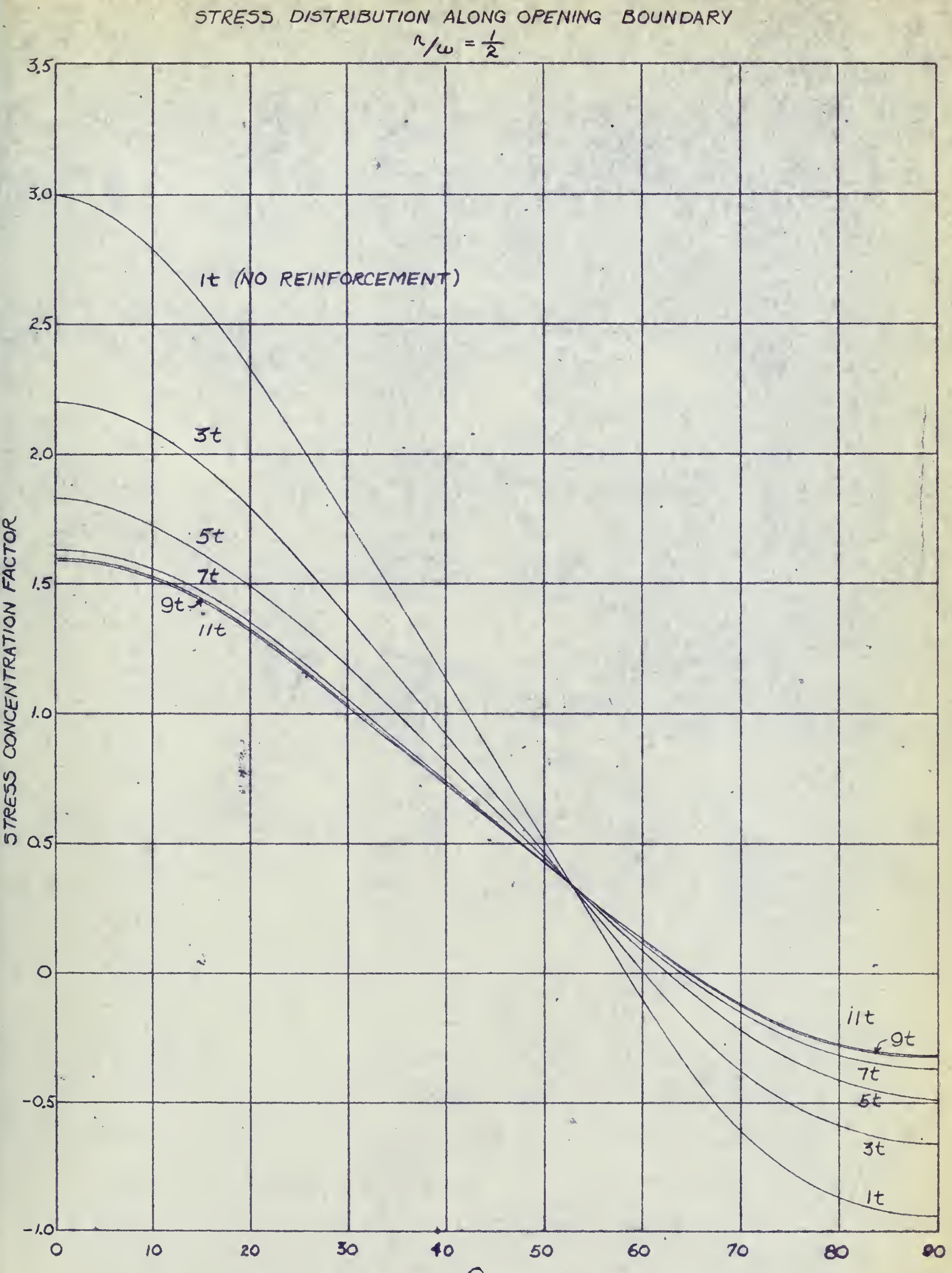


FIGURE 18


STRESS DISTRIBUTION ALONG OPENING BOUNDARY
r/ω = 1/2
STRESS CONCENTRATION FACTOR
θ
1t (NO REINFORCEMENT)
3t
5t
7t
9t
11t
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
-0.5
-1.0
0
10
20
30
40
50
60
70
80
90
FIGURE 19

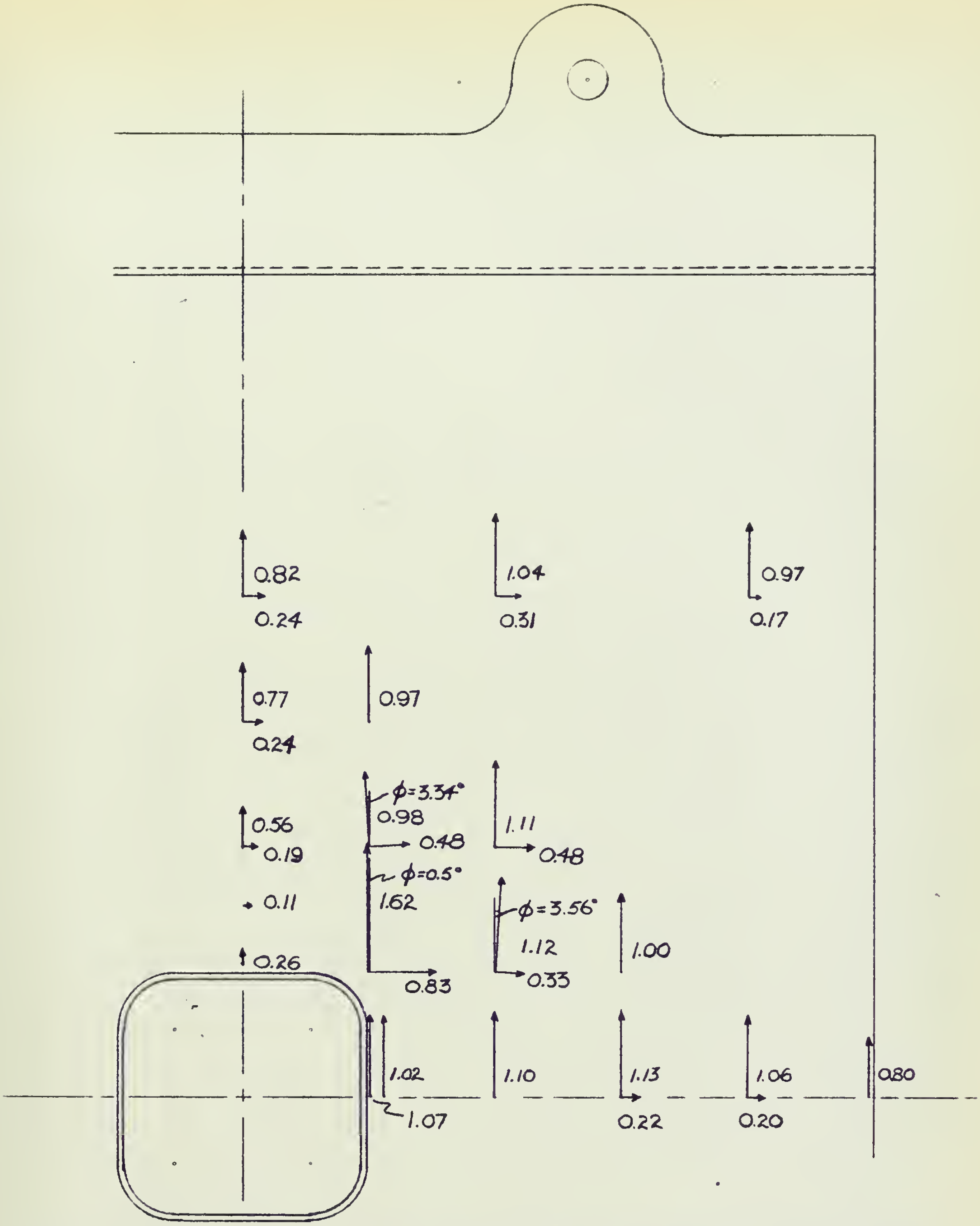
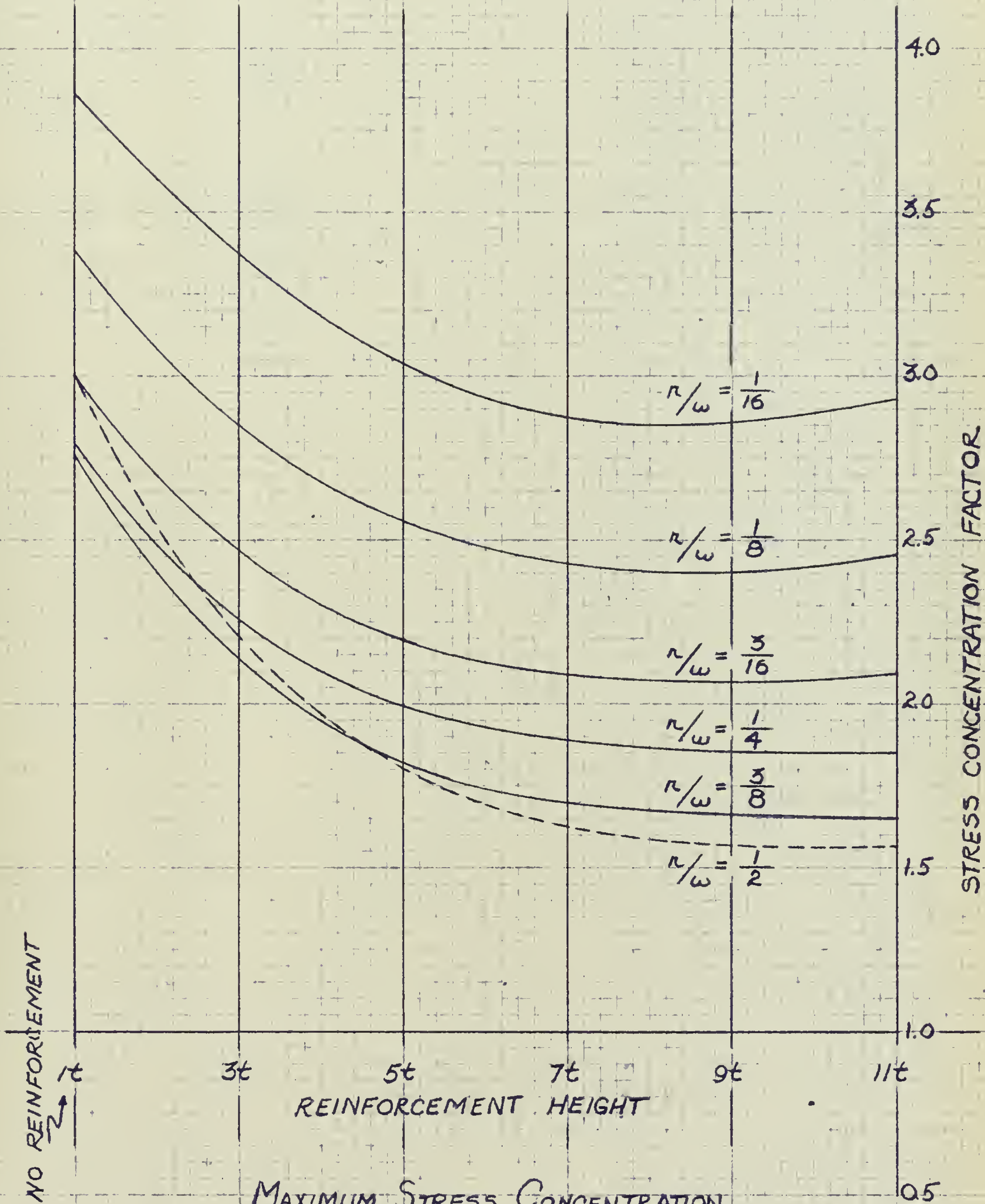
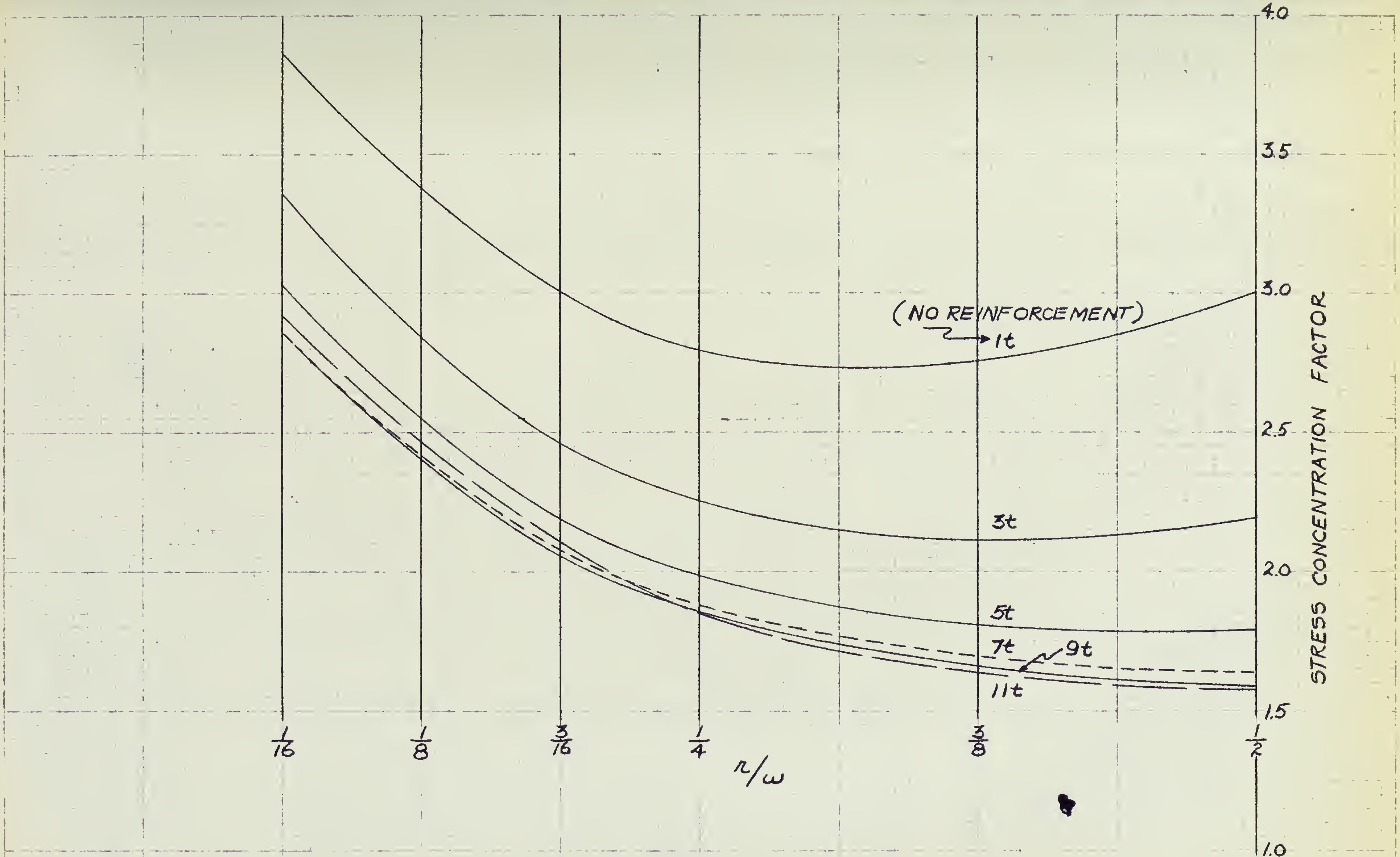


Figure 20 - Typical example of stress distribution in the plate proper. The case shown is for specimen #4 ($r/w = \frac{1}{4}$) with a reinforcement height of 9t. The principal stresses for three locations have been computed from strain rosettes and the directions are as indicated by the angle ϕ. All values are shown in terms of stress concentration factor.



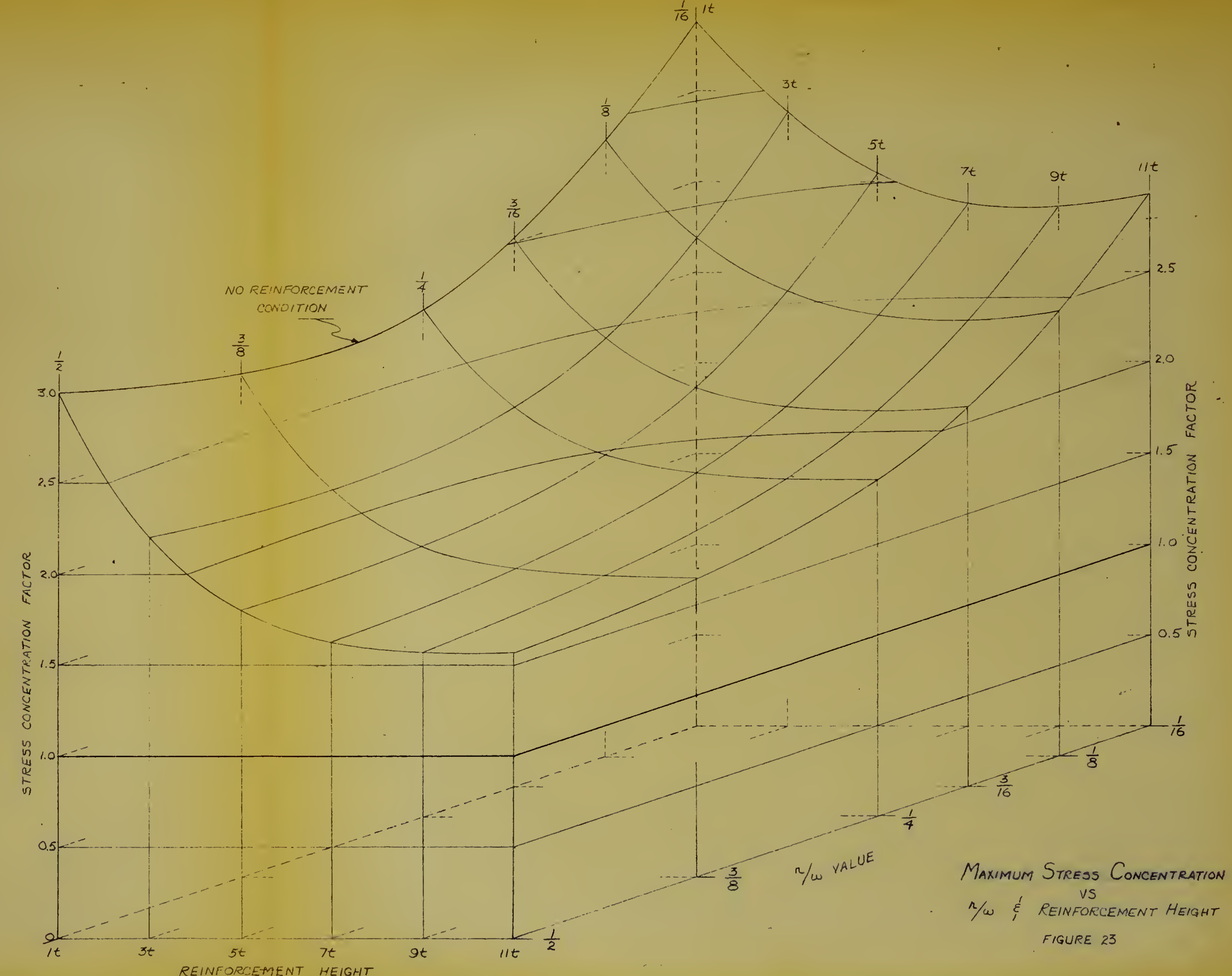
MAXIMUM STRESS CONCENTRATION
VS
REINFORCEMENT HEIGHT

FIGURE 21



MAXIMUM STRESS CONCENTRATION VS r/w

FIGURE 22



MAXIMUM STRESS CONCENTRATION
VS
r/w & REINFORCEMENT HEIGHT

FIGURE 23

V. DISCUSSION OF RESULTS

A. STRESS-STRAIN RELATION

In order to determine either the stress or strain concentration factor the slope of the load-strain curve was determined. The slope was obtained by plotting the summation of the change in strain reading against the corresponding total change in load. The strain concentration factor was then calculated as the ratio of the slope of the load-strain curve to the slope that existed, in the direction of the applied load, in the plain plate. The stress concentration factor was then taken as equal to the strain concentration factor, for the reasons which are discussed in the following paragraphs.

As the load was applied it was observed that at first a non-linear relationship occurred between the measured strain and the applied load but it became linear at higher loads. This was directly due to the warpage in the plates as a result of the welding. Thus, it was necessary to conduct tests in a load range such that, at certain points in the specimen, stresses approached the proportional limit or even surpassed it.

For the maximum load applied to the plates, 90,000 pounds, a strain concentration of 3.33 would mean that at that location the proportional limit would be reached.

In those cases where concentrations of greater than 3.33 were reached the final results were unaffected. In a region which reaches the yield point, as the applied load causing

yield is removed, the unloading strain-load curve follows Hooke's law. This unloading curve is parallel to the Hooke's law curve existing before yield. On succeeding cycles, remaining within the previous load range, there is no deviation from the unloading curve. This was confirmed by checking some of the gages during testing. Similiar conclusions were reached by George E. Griffith (7) with the one notable difference that the slope of the unloading curve was observed to become gradually shallower as the maximum strain is increased. The difference between Griffith's observation (7) and those of this investigation is attributed to the relative amount of total permanent set; the set was only a small percentage of the strain in this investigation.

In a limited number of cases, a value of slightly more than 3.33 was reached. In these cases yielding did not occur but the last points of the strain-load curve showed a non-proportional relationship. However, there were sufficient experimental points to determine the proportional slope.

Since the elastic slopes could be determined the relation between stress and strain can be simply stated. Although an axial load is being applied to the specimen, elements of the material near the opening can be considered as being acted upon by a biaxial loading system. The stress-strain relation, assuming that the steel is a isotropic

material, is:

$$S_1 = \frac{E(e_1 + ue_2)}{1-u^2}$$

Thus, the principal stress S_1 can be determined if both principal strains are known. However, for the locations of principal interest in this investigation it was not necessary to know e_2. For those gages located along the boundary of the opening, it seems reasonable to assume that e_2 equals $-ue_1$ because the reinforcement edges are free, in which case the above equation reduces to:

$$S_1 = Ee_1$$

Since the stress is directly proportional to the strain, then a ratio of stresses (stress concentration factor) would be equal to the ratio of the corresponding strains (strain concentration factor).

In the plate proper the assumption that e_2 equals $-ue_1$ could not be made. However, for reasons of simplicity it was desirable to continue to use the expression:

$$S_1 = Ee_1$$

where S_1 now is considered to be a "virtual" stress. Several theories exist, known as "theories of failure", which compare the conditions in a biaxial stress situation with a corresponding limit evaluated from a uniaxial test of the material. For ductile materials the current practice is to use the maximum shear theory of Guest or the shear distortion theory of Hencky-von Mises, the latter being in best agreement with

test data (8). In this investigation, the magnitudes of the stresses in the direction of the applied load are large compared to the transverse stresses so that there is little difference in the results obtained from several of the various "theories of failure". For reasons of simplicity it is desirable to use Saint Venant's maximum strain theory. This theory predicts values, in the region of interest, close to those of the Hencky-von Mises theory.

The maximum strain theory is based on the assumption that failure will occur at a point when the maximum principle strain being experienced by the material at that point reaches the value of the limiting strain as determined from an axial test. This condition can be expressed in equation form as

$$e_1 = \text{limiting } e$$

If both sides of the equation are multiplied by the modulus of elasticity, then

$$S_1 = \text{limiting } S$$

where S_1 is a "virtual" stress. Therefore, the stress concentration factor can be taken as equal to the strain concentration factor for this investigation.

The principal strain directions along the axial and transverse axes and along the boundary of the opening are known from symmetry considerations. The symmetrical nature of the strain pattern about the axes was checked during the tests. Rectangular strain rosettes were used to determine principal strains at other important locations in the plate proper.

The strain readings when using SR-4 strain gages are affected by the transverse sensitivity of the gage (9). The gages are calibrated to account for the normal Poisson effect. Since the error produced by this effect for gages orientated in the direction of the applied load is less than one percent, no correction was made. Gages mounted on the reinforcement were unaffected by transverse sensitivity since the gages were subject to conditions similiar to those of the gage calibration.

In the case of the transverse orientated gages, the transverse sensitivity results in readings which are estimated to be in error from 13% for the A-5 gages to 4% for the A-7 gages. These readings were of low order compared to the concentration values in the direction of the applied load. Therefore they were of little significance and no attempt was made to correct them. The following formulas can be applied to correct this error if desired. These formulas are applicable to all gage readings and are not limited to those transversely orientated to the axial load.

$$k_a = k_a' - Kk_b' \qquad S_a = \frac{E}{1-u^2}\left[e_a'(1-uK) + e_b'(u-K)\right] \quad *$$

where K = 0.035 for A-5 gages and K = -0.010 for A-7 gages (9).

---

* In retrospect an opportunity was overlooked by the authors to obtain a check on the value of Poisson's ratio by the placement of transverse gages on the plain plate. The lack of

B. COMPARISON WITH EXISTING THEORIES

The experimental results were compared with three applicable theories, Brock (3) for the unreinforced square opening with rounded corners, Timoshenko (5) for simplicity of application to the unreinforced circular opening case, and Reissner and Morduchow (10) for the reinforced circular opening case ($r/w = \frac{1}{2}$).

In testing specimen #6 ($r/w = \frac{1}{2}$), the specimen containing the circular opening, the experimental distribution of stresses around the opening on the reinforcement followed the expected pattern except for the cases of 1t and 3t reinforcement height. As a quick check Timoshenko's equation was used for values of the 1t reinforcement height condition of specimen #6 ($r/w = \frac{1}{2}$) i.e. plate with an unreinforced circular hole (5).

$$k_\theta = 1 - 2\cos 2\theta$$

This check indicated a deviation from theory for this condition.

As a further check on the stress pattern for this plate the Reissner and Morduchow paper of reinforced circular cutouts in plane sheets was used as a theoretical check (10). It should be noted that Reissner and Morduchow (10) predict results identical to those of Timoshenko (5) for the unreinforced (1t) case. Figure 24 shows a comparison of the experimental data with the Reissner-Morduchow distributions.

sufficient time precluded the authors from collecting this additional information.

COMPARISON OF EXPERIMENTAL CURVES WITH THEORY

$r/\omega = \frac{1}{2}$

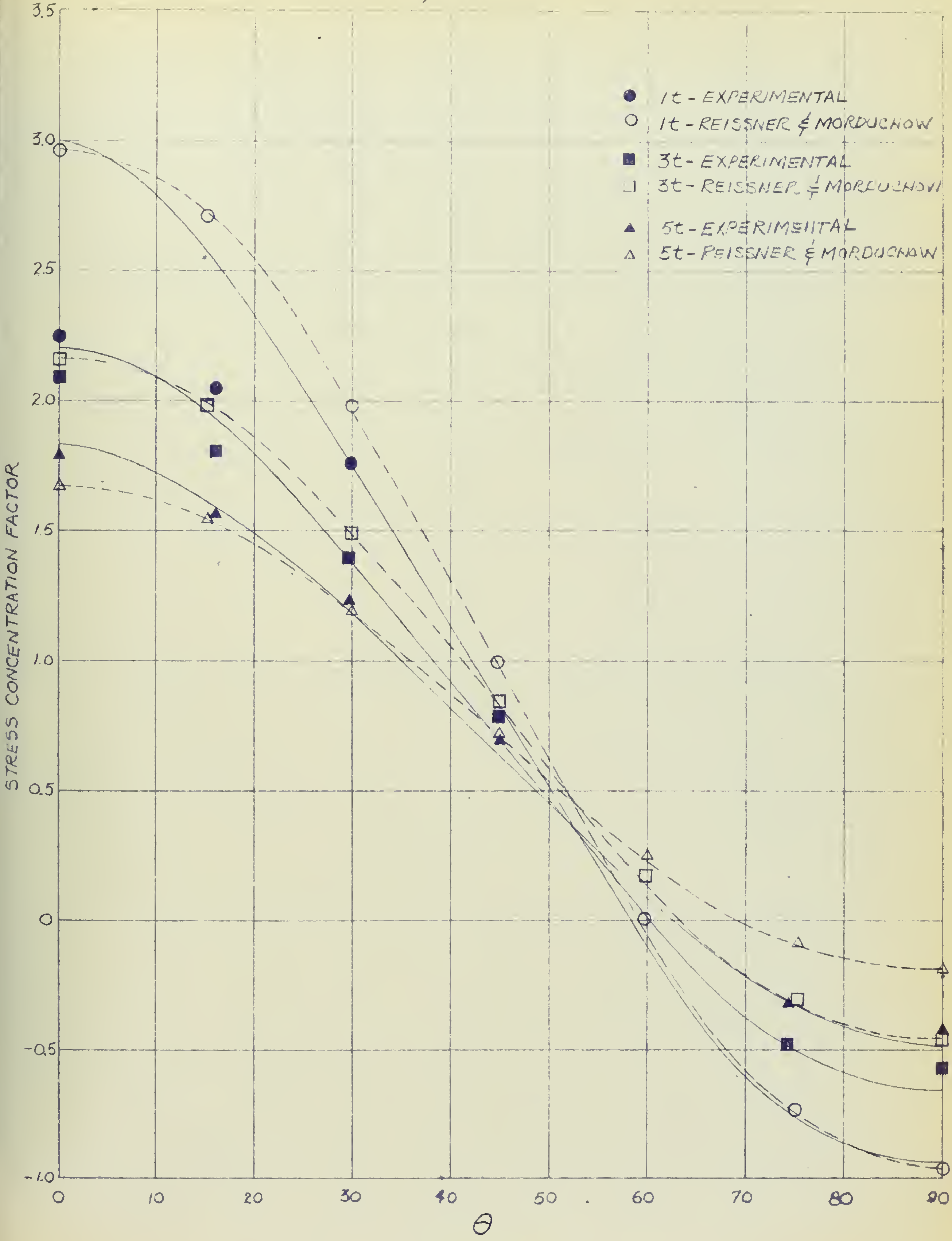


FIGURE 24

Reasonable agreement is indicated with theory except for the 1t and 3t reinforcement height cases in the region approaching the maximum concentration value.

The 9t and 11t reinforcement maximum concentration points were also checked with Reissner and Morduchow. These two points were used because the strain distribution along the height of the reinforcement was known. The average strain concentration factor was obtained by integration using the trapezoidal rule. These values differ from the theory by the same approximate amount as the maximum point for the 5t case as shown in the following table.

TABLE II

Comparison of

Theoretical and Experimental Concentration Factors

Reinforcement height	1t	3t	5t	9t	11t
Experimental	2.24	2.08	1.78	1.18*	1.02*
Reissner-Morduchow	2.97	2.16	1.67	1.10	0.92
Timoshenko	3.00	-	-	-	-

* These are integrated values.

As a cross check a comparison plot of the 1t transverse distribution across the intact width of the specimen was made with Timoshenko (5). These plots show close agreement except near the maximum point, Figure 25.

As a further check on the circular case and a check on the square openings the axial strain concentration distribution

COMPARISON OF EXPERIMENTAL RESULTS WITH THEORY

$r/w = \frac{1}{2}$; 1t

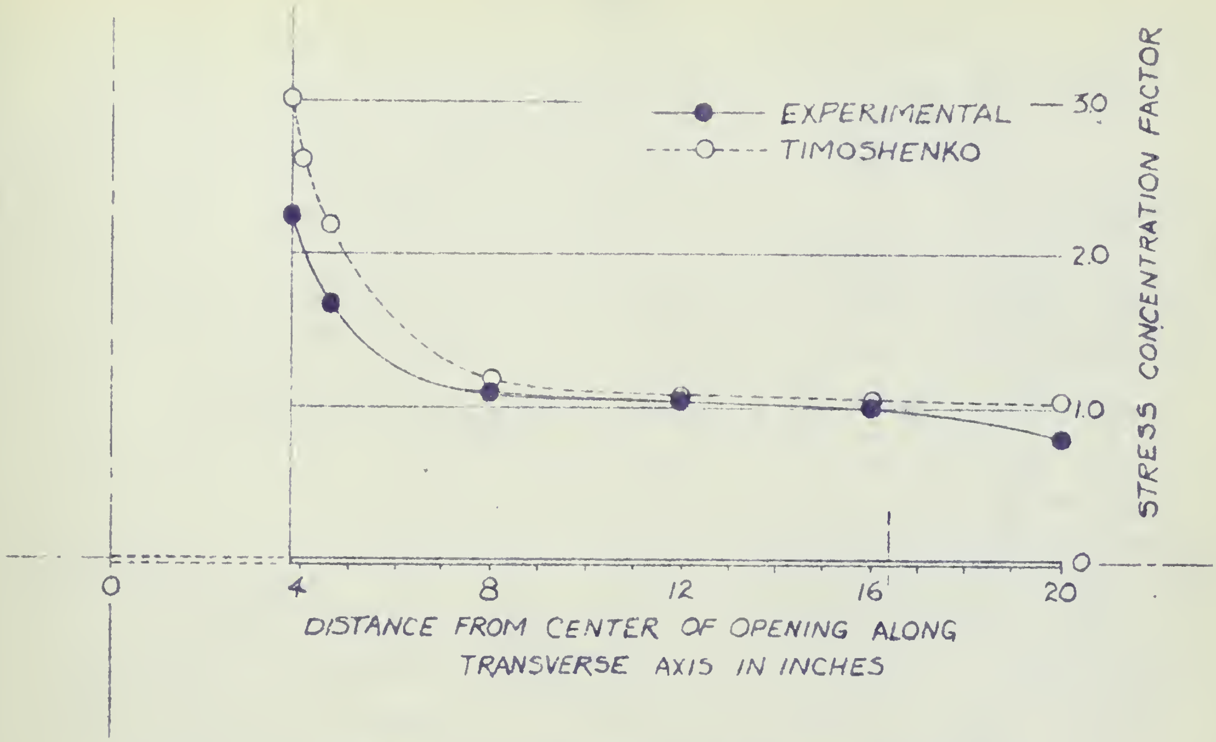


FIGURE 25 - STRESS DISTRIBUTION ALONG TRANSVERSE AXIS

along the transverse axis through the center of the opening was integrated by use of the trapezoidal rule and an average strain concentration obtained. The required average strain concentration based on the applied load and the intact cross sectional area was then computed and comparisons made. The required average strain concentration value was computed as the ratio of the cross sectional area before the opening was made to that area remaining including the reinforcement area. These comparisons show that the results obtained for specimen #1 (r/w = 1/16) through specimen #5 (r/w = 3/8) are satisfactory. However, for specimen #6 (r/w = ½) there is an indicated error for the 1t and 3t conditions. In these cases,

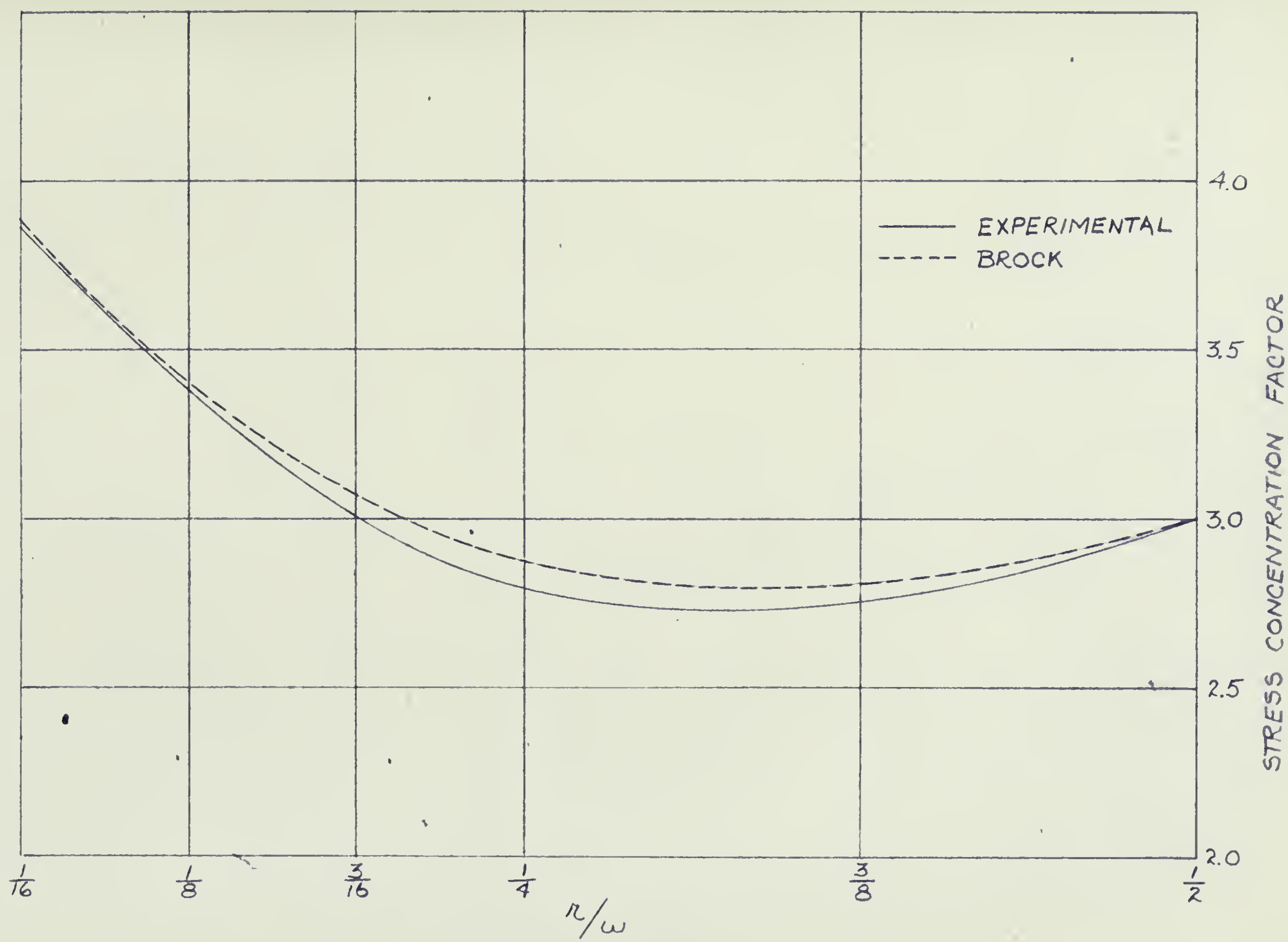
using the theoretical values for the gages having the largest deviation from the theoretical values, reintegration results in a value close to those required.

Based on these studies and comparisons with the existing theories the discrepancy is localized at the boundary of the opening near the maximum point. This discrepancy is attributed to gage failures and is probably due to heat produced during the milling operation. The theoretical values for the maximum points for the 1t and 3t cases were used in plotting the curves for the results of this investigation in lieu of the measured values for specimen #6 ($r/w = \frac{1}{2}$). These curves are shown in Figure 24 for comparison with theory.

Figure 26 shows a comparison of the maximum stress concentrations for the unreinforced square openings with that of Brock (3). Also, the stress distribution along the boundary of the opening compares favorably with that predicted by Brock as can be seen from Figures 13 and 27.

C. ACCURACY

As a result of the error involved in the test results of the specimen with the circular opening, the validity of the curves for which there is no existing theory was considered. The experimental procedure was capable of reproducing meter readings to within ± 2 microinches per inch. This was checked at random throughout the test series and this reading repeatability was possible regardless of the condition of the test. When gages needed to be replaced, differences could be



COMPARISON OF EXPERIMENTAL RESULTS WITH THEORY

MAXIMUM STRESS CONCENTRATION VS r/ω
FOR It (NO REINFORCEMENT) CONDITION

FIGURE 26

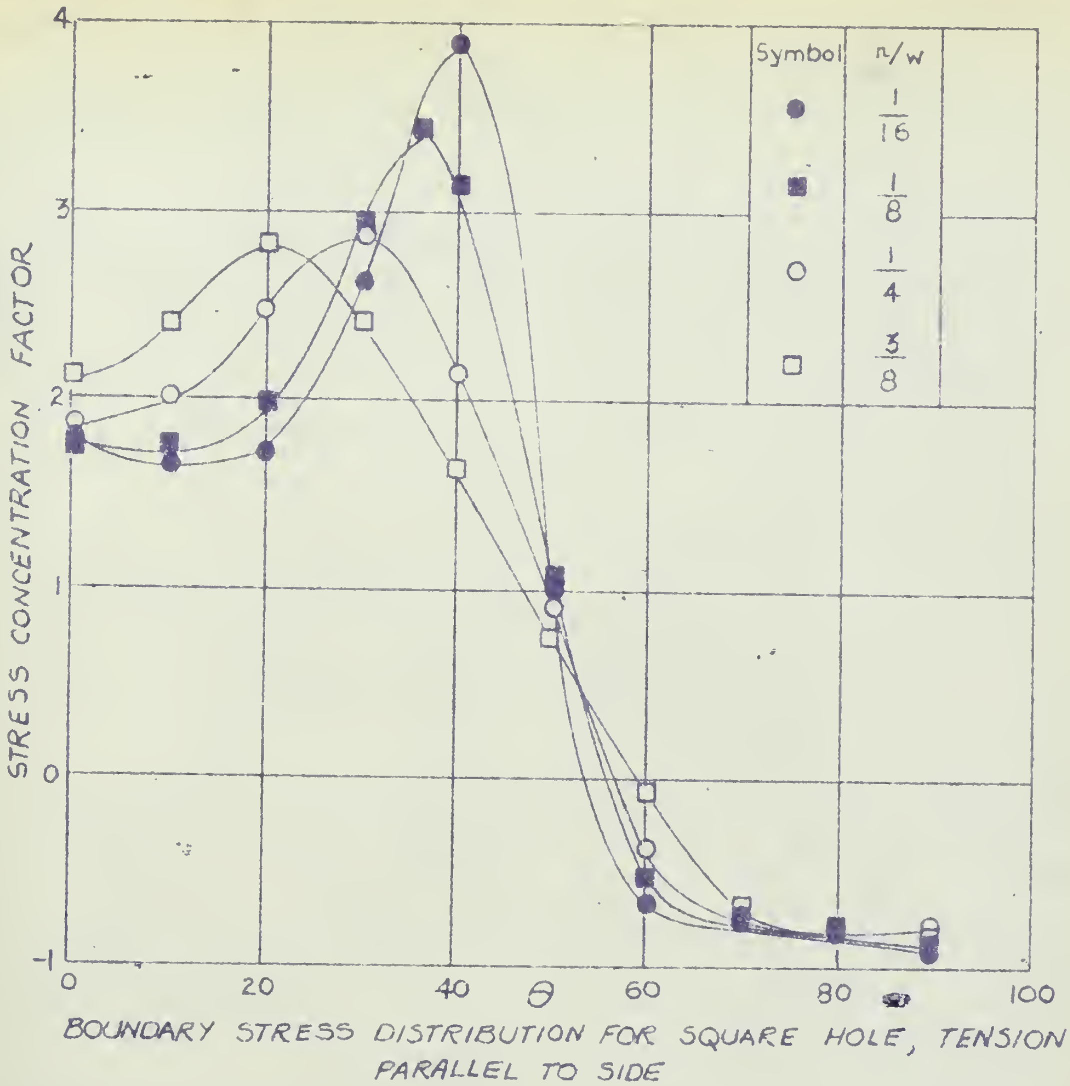


Figure 27 - Stress distribution along boundary of unreinforced (1t) opening predicted by Brock (3). This is Figure 5 of reference (3) reproduced with the permission of the author. For clarity in comparing with Figure 13 of this investigation, symbols have been changed and the curve for r/w = 1/32 omitted. It is noted that Brock did not include curves for r/w = 3/16 and r/w = 1/2.

detected. However, the differences were within the limits of the experimental accuracy discussed later. The following are conditions under which repeatability was checked.

1. Removal of the specimen from the testing machine and without milling the reinforcement replacing the specimen in the testing machine with adjustment of the clevises.
2. Relocation of gage leads at the switching box or between switching units.
3. Rerunning of the test on a different day.

Air temperatures were normally in the region of 70 to 72°F though no special precautions were taken as to temperature except attempting to insure that the heating system was not operating during a test so as to avoid directing a flow of air onto the specimen. Due to the physical location of the equipment such a flow was possible and there were times when accidental operating of the heating system resulted in checks which indicated that the errors induced are negligible.

The justification for acceptance of the low order concentrations is based on this repeatability of the procedure.

As discussed in the previous section an integration of the axial strain concentration distribution across the transverse axis was made for all the specimens as a check on the overall accuracy. This integration also served as a check on the symmetrical loading of the specimens since the

integration was conducted over only half of the transverse symmetrical axis. A further check on the symmetry of the load was provided by the placement of check gages on specimen #4 ($r/w = \frac{1}{4}$).

In view of repeatability of the gage readings and based on the integrated strain concentrations it is believe that the overall accuracy of the results is within ten percent. In stating that there was repeatability of the readings in no way is it meant that a second specimen of a given r/w ratio would give exactly the same readings, due to unavoidable differences in fabrication and exact gage locations.

It is reasonable to expect that out of the large number of gages applied that some percentage would fail to give satisfactory results. In this regard, particular reference is made to the gage plotted at 40° on specimen #2 ($r/w = 1/8$) and the gage plotted at 31.5° on specimen #3 ($r/w = 3/16$). Taking into proper perspective a percentage of gage failures and the inherent accuracy of an SR-4 gage itself, there remain two factors peculiar to these tests which entered into the overall accuracy given above.

The first is the condition of the specimens. There were locked-in stress due to the welding of the reinforcement and the welding of the specimen strongbacks. It is the opinion of the authors that the combination of cycling the load and the vibration of the milling operation relieved the locked-in stresses so that only the initial test of each specimen would

have been effected. This was indicated by the larger amount of scatter of points in Figure 8 than for the same gages in Figure 9. The welding, however, produced a secondary effect and that was physical distortion of the plate proper of the specimen. This was indicated by the difference in the readings between the two gages in those locations which were backed up. Specimen #5 (r/w = 3/8) was particularly affected by this in the plate proper. In most other cases this was a minor problem with the large loads used. Testing of specimen #1 (r/w = 1/16) was conducted at somewhat lower loads so as not to have too large a permenent set in the material and as a result bending of the plate proper was still observed.

The second effect on overall accuracy is the milling operation. This was not the accuracy of the cut but rather the dangers produced in having to mill the reinforcement. Two problems were involved; both concerned with the loss of the gages on the edge of the opening. Specimen #4 (r/w = ¼) was the first specimen tested and the method of leading the wires from the gages on this specimen resulted in loss of most of the reinforcement gages. In succeeding specimens a thin plywood board was glued into the opening and the wires from the reinforcement gages taped to this board. With this method the worst that could happen was the loss of a gage due to its lead being milled off.

On the second specimen to be tested, specimen #5 (r/w = 3/8) it was learned that the weld material offered a resistance

to the cutter of such a magnitude that frictional heat burned the gages. Part of these difficulties were due to the fact that the milling was being done by a portable milling machine mounted on an alignment jig. This eliminated a lot of handling and wiring problems but presented a few milling oroblems, limited experience being the major contributor to the difficulties.

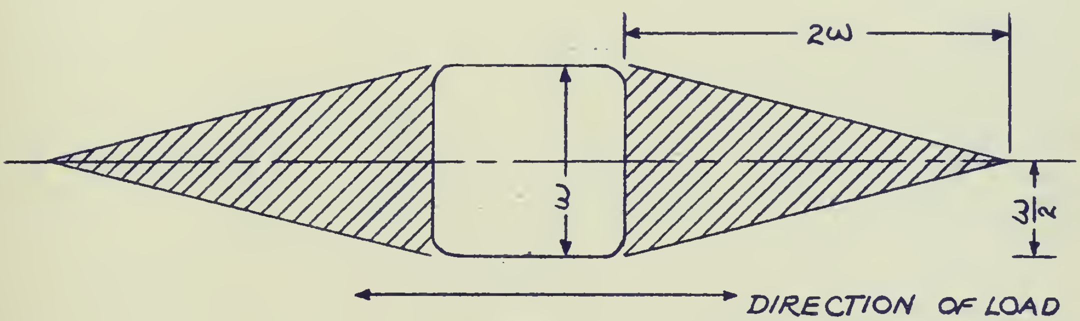
Specimen #6 ($r/w = \frac{1}{2}$) was the third plate tested and although no gages were lost it was apparent that the solution to the heat problem was freshly sharpened milling cutters. Feed, revolutions per minute, and cooling fluids had minor effects, and usually were restricted by other considerations. On the remaining specimens the cutters were changed more often than on specimen #6 ($r/w = \frac{1}{2}$), and there was no more trouble. Since lost gages were replaced on specimen #4 ($r/w = 1/4$) and #5 ($r/w = 3/8$) the accuracy of the results of these specimens is comparable to the other specimens.

D. STRESSES IN THE PLATE PROPER

In the preceeding sections some mention has already been made of the plate proper. It was pointed out that the gages transversely orientated to the applied load give measured strain errors ranging up to 13% which error can be corrected by the application of the formula on page 17. Even without correction, the gages parallel to the applied load give values within the overall accuracy of ten percent previously discussed.

The plate proper was not instrumentated to a great enough extent to be able to describe completely the stress pattern therein. There are trends however, indicated by the data. Figure 20 is a representative case. Those of the other specimens show comparable patterns except as noted below.

As can be seen from Figure 20 there is a definite shirking of the load along the y-axis of the specimen. Based on rosette measurements at (x=4;y=4) and (x=4;y=8), there are indications that the area of material shirking the load is similiar in size and shape to that assumed by the shadow rule in Bureau of Ships Design Data Sheet DDS 2900-1-n, paragraphs 3 and 4.



The remainder of the plate proper is relatively unaffected by the opening except for a narrow band which borders the combined opening and shadow area. The stress field outside of the band is increased less than 10% at its point of greatest concentration over that which would exist without the opening. It is concluded from this that the ratio of the width of plating to width of opening assumed on page 4 was sufficient so as not to effect the stress pattern and values in the region

of the opening. At any transverse section since there is a certain average stress which the specimen must carry and to compensate for the load carrying ability lost by the section as a result of the opening or shadow area, the stresses in the band which borders the opening and shadow area increase in value. As a result of the lack of gages in the plate proper, the stress pattern in the band along the shadow area and opening is not clearly defined. It is known from the pattern of the gages available that the maximum stress concentration in the plate proper is located in that portion of the plate proper along the side of the opening which is parallel to the direction of the applied load. Its location and magnitude is affected by the choice of corner radius and reinforcement height. The maximum stress concentration in the plate proper is always less than the maximum stress concentration value along the boundary of the opening in each particular case.

E. COMPARISON WITH DDS 1100-1

The Bureau of Ships Design Data Sheet 1100-1 is a guide for designing reinforcement around openings in structural members. The required reinforcement is based on the thickness of the plating and the size of the opening. For shell and deck plating within the midships three-fifths length, and for the size of opening and thickness of reinforcement used in this investigation, DDS 1100-1 gives the following dimensions:

Reinforcement Height $\approx 8t$

Corner Radius $\approx 1/4$

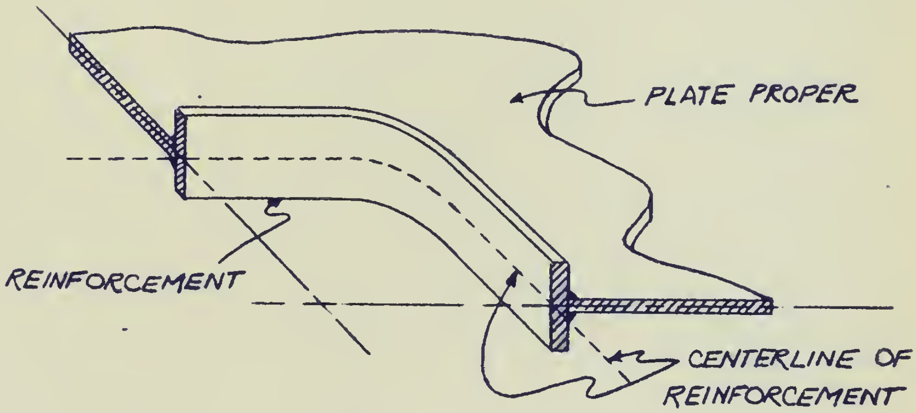
Entering Figure 22 this results in a stress concentration factor equal to 1.87.

F. CONCLUDING REMARKS

Figures 8 to 19 were obtained on the assumption that the variation of the stress concentration factor with changes in the corner radius and reinforcement height obeys the rules of a continuous function. Thus, the curves in the figures were constructed by cross plotting each point against the r/w ratio and the reinforcement height, producing smooth curves. Figure 21 and 22 are representative of such curves.

On the basis of this method of plotting and as a direct result of the loss of gages the following cases are extrapolated curves using the few points available as a check, specimen #4 (r/w = 1/4), #5 (r/w = 3/8) and #6 (r/w = 1/2) for the 1t reinforcement height.

The stress concentration factors plotted in Figures 8 to 19 and Figures 21 to 23 are located along the centerline of the reinforcement as shown in the accompanying sketch.



On specimens #4 ($r/w = \frac{1}{4}$) to #6 ($r/w = \frac{1}{2}$) gages were located near the edges of the reinforcement for the 9t and 11t cases. These gages showed that the stress is not distributed uniformly across the height of the reinforcement but rather that it falls off near the edges. This falling off at the edges is further indicated by Figure 21 which shows that reinforcement heights greater than 7t have only a minor effect on the maximum stress concentration.

VI. CONCLUSIONS

A. CONCLUSIONS WITH RESPECT TO THE INVESTIGATION

1. The results define very well the stress distribution and values along the boundary of the opening.

2. The results agree well with the following theories:

    a) J.S. Brock (3) for unreinforced square openings with rounded corners.

    b) Reissner and Morduchow (10) for the reinforced circular opening.

3. The loading arrangement, measurement system, and milling arrangement all functioned very well.

4. The specimen was of sufficient size so that with the loading arrangement used the stress patterns and values in the region of the opening were independent of the specimen boundaries.

5. Field stress patterns and values could have been better defined by the use of more gage locations and back-up gages.

6. The overall accuracy of the results is ten percent.

7. The principal factors which contributed to the above accuracy are the inherent gage accuracy and the distortion of the specimen from a plane surface as a result of the welding.

B. CONCLUSIONS WITH RESPECT TO THE DESIGN OF A SQUARE OPENING REINFORCED BY A FLAT BAR

1. In the design of a reinforced square opening a considerable range of choice of corner radius and reinforcement height is available to keep the concentration factor down to a reasonable value.

2. The minimum possible value of the maximum stress concentration factors is 1.56.

3. There is a maximum practical reinforcement height above which additional height has little effect on the maximum concentration value. For a reinforcement thickness equal to the plate thickness this value is seven times the plate thickness.

4. The maximum stress concentration is located on the boundary of the opening.

5. Bureau of Ships Design Data Sheet 1100-1 recommends a combination of minimum corner radius and minimum reinforcement height which is a reasonable lower limit.

VII. RECOMMENDATIONS

1. It is recommended that an investigation of this type be conducted for other reinforcement thicknesses.

2. It is recommended that an investigation of this type be conducted for rectangular openings with rounded corners.

APPENDIX I

DETAILS OF DESIGN

A. GENERAL

The primary consideration in the design of the specimen and accessories was to obtain a specimen of maximum size consistent with the capacity of the equipment and facilities available for this investigation. Consideration to time and effort was also taken with regards to the utilization of the equipment and the handling of the specimen. To these ends a survey was conducted of the then existing equipment and facilities. The following was found available.

1. The Engineering Laboratory is a newly constructed laboratory with a Baldwin-Southwark 200,000 pound universal hydraulic testing machine.

2. The Machine Shop had available an assortment of light machines, the following being of direct interest:

    a. No. 2MH Cincinnati Milling machine.

    b. Arc welding and gas burning equipment.

The normal method for application of a tensile load to a specimen of this type in the Baldwin testing machine was by means of a single clevis attached to the upper and lower crossheads. If this method of attachment had been used the

distance available in the direction of loading to distribute the concentrated load of the single clevises into a uniform stress and for a uniform test area would only be 54 inches. This was considered unsatisfactory for obtaining reliable results. Other methods of coupling the specimen to the Baldwin testing machine which would maximize the size of the specimen were studied. The two point coupling method used was considered the most feasible.

The choice of the method of coupling to the testing machine was also related to the ability to machine the specimen reinforcement and to obtaining an infinite width effect from a finite width plate. A relationship between width of opening to width of plate was choosen so as to minimize the effect of the finite width of the specimen. The value was based on the conclusions of references (4) and (5) which stated that the stresses around the opening will be independent of the plate width if the plate width is greater than or equal to five times the opening width. The Cincinnati milling machine had a reach of 24 inches. For minimum handling effort, it was desirable to do the milling with only one set-up operation per side. Thus:

$$\frac{\text{width of specimen}}{2} + \frac{\text{width of opening}}{2} = \text{reach of milling machine}$$

$$\frac{1}{2}\left(\frac{\text{width of specimen}}{1} + \frac{\text{width of specimen}}{5}\right) = 24''$$

$$\text{width of specimen} = 40''$$

This width was quite satisfactory for the coupling method used. (See design of coupling system.)

By this time sufficient rough dimensions were available to design the specimens. The specimen plans were sent to David Taylor Model Basin, Carderock, Maryland for the fabrication of the specimens.

The utilization of the Cincinnati milling machine and the design of a milling jig to use with it met with many problems. The limiting one was dead weight to be supported. The total specimen weight was estimated at about 330 pounds with 90 pounds concentrated at each end of the specimen in the form of a strongback. It was the feeling that with the machine available, the weight distribution would make accurate milling difficult if not dangerous to the machine. In addition the transfer of the fully instrumentated specimen between the two buildings, in both physical effort and time involved could not be ignored. It was felt from the start that the ideal set-up would be to do the milling in or near the testing machine. As a result of effort towards this end the loan of a Versa-Mil, a portable milling machine, was obtained from New York Naval Shipyard. This made it possible to mill the reinforcement within $\pm$ 0.005 inches without disconnecting measuring equipment and with minimum handling of the specimen weight. Figures 28 and 29.

Figure 28 - Relative position of milling operation with respect to the testing machine. Note the overhead rail running under the upper machine crosshead.

Figure 29 - Milling operation in progress showing Versa-Mil and foundation jig structure.

It was decided that a $\frac{1}{4}$ inch thick plate would be used for the specimens. Concentration factors of three to four were predicted and therefore the maximum applied load, based on the cross-section of the specimen, when yielding occurs was estimated to be 100,000 pounds. This was used as the design load.

B. COUPLING SYSTEM

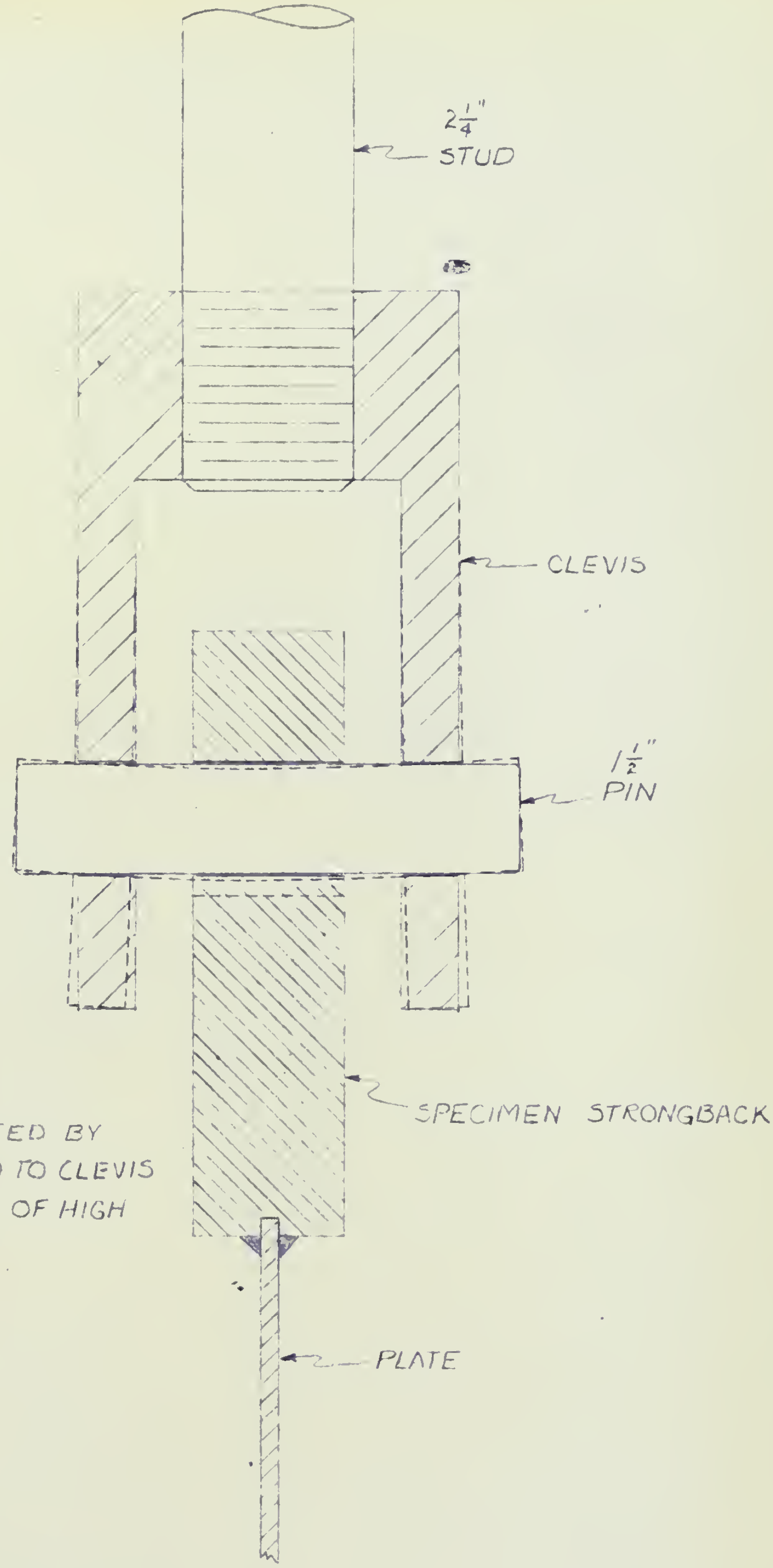
The desire for the maximum specimen length possible was based on having a uniform stress distribution, at least in way of the opening area. The two point coupling system easily produced this condition. This method of coupling uses 90% of the available distance between the machine crossheads as well as attempting to introduce a uniform load, by means of a specimen strongback, at the specimen edge.

It is to be noted that the lateral constraint imposed and the distortion involved in the welding of the specimen strongbacks are disadvantages. However, the results of the testing of specimen #7 show these to be negligible.

Figures 4 to 6 show the general arrangement and nomenclature. The Baldwin testing machine applies a tensile load by moving the upper machine crosshead away from the lower crosshead. With the coupling crossheads as shown, they are moved apart transferring the load to the specimen strongbacks via the clevises. Since removal of the speciman from the testing machine after each test was necessary, pins were used to facilitate the procedure.

The choice of scantlings for the specimen strongback were based on (1) the maximum width of the specimen of 40 inches, (2) the minimum distance between the pin center lines of 22 inches, and (3) acceptable deflections of the strongback. By considering the strongback as a beam carrying a uniform load simply supported at two points, it was calculated that regardless of the moment of inertia the deflections at the ends and mid points relative to the pins were the same. Due to materials available the specimen strongbacks constructed had a moment of inertia of 15.2 $inches^4$ producing calculated deflections of 0.00446 inches. Since the specimen proper would act as a web to the strongback these deflections would be appreciably lower.

The other components of the system were checked for strength in similiar ways. The only component to fail under testing of the equipment were the pins. The pins and clevises used were part of the available laboratory equipment. These failed mainly as a result of their span and the looseness of fit. Under the action of the load the pins and clevises assumed the configuration shown in Figure 30. It was desired to maintain a loose fit for ease of handling, thus the first corrective measure was to cut the span by welding two 3/4 inch thick steel plates to the clevis. In addition the strength of the pins was increased by the use of high yield steel, HY-100, in lieu of mild steel.



NOTE:
PIN FAILURE CORRECTED BY
3/4" SPACERS WELDED TO CLEVIS
AND SUBSTITUTION OF HIGH
YIELD STEEL PIN.

FIGURE 30

PIN FAILURE WHICH OCCURED DURING TESTING OF APPARATUS

C. <u>SPECIMEN DESIGN</u>

The design of the coupling system and the specimen were interdependent. However, once the method of coupling and some dimensions were fixed, it was possible to design the final specimen.

The coupling system made it possible to make-up the coupling clear of the machine crossheads, Figures 4 to 6. Thus, the overall length of the specimen and specimen strongbacks could be greater than that needed between the machine crossheads during the test by the height of the coupling ears on the strongback. A first estimate of overall length was made by measuring the diagonal of the opening through which the specimen had to pass into the testing machine. The lower crosshead was positioned just off the table in order to obtain maximum clearance for the specimen.

Using this as an overall dimension and the previously designed specimen strongbacks there was available, between the table and bottom of the lower machine crosshead, 7 inches. In the application of the tensile load the lower crosshead and table move together and thus a margin for travel was necessary. Based on the design conditions it was estimated that travel would be less than a tenth of an inch. Since the travel of the machine was negligible it was only necessary to assure sufficient room for the coupling strongback and the making up of the coupling. The lower strongback was designed to fit with a 1 3/4 inches clearance for a margin. In making up the

lower coupling it was necessary to have sufficient room to start the nut and make it up at least flush with the stud. Standard 2¼" finished hexagon nuts were used and the space available for making up was sufficient.

This finalized the design and the plans were sent to David Taylor Model Basin for construction of specimens. Specimen strongbacks were welded to specimen #4 and #7 at David Taylor Model Basin, the welding being done on a welding flat. Welding of the specimen strongbacks to the remaining specimens was accomplished at Webb Institute of Naval Architecture. A welding flat was not available but by machining a close fit groove in the specimen strongback to take the specimen, good alignment was accomplished at a cost of a ½ inch of specimen length.

D. MILLING MACHINE FOUNDATION AND JIG

To use the Versa-Mil for milling operations at the location of testing, the first idea was to mill the specimen while it was in the testing machine. Among other problems, the interference of the testing columns and the fact that a foundation and jig would have to be a structure 6½ feet high made such an idea inadvisable.

Since the authors had planned on using an overhead rail for handling the specimen it was decided to use this in conjunction with a combination milling machine foundation and jig. The method used was to support the weight of the specimen

from the overhead rail and use a single structure to support the machine and hold the specimen in proper alignment. See Figures 29 and 31 to 33.

Figure 31 - Specimen entering milling jig. Handling gear shown at top of picture is also used to support the weight of the plate during the milling operation.

Figure 32 - Versa-Mil and back-up plate. Note cutout to permit wires from reinforcement gages to be led clear when specimen is clamped to back-up plate.

Figure 33 - Specimen clamped to back-up plate with a bar strongback ready for final milling cut.

As shown in Figures 31 and 32 the Versa-Mil was set on a foundation in such a position as to locate the milling cutter opposite a back-up plate. This plate was 8" x 8", just large enough to set the reinforcement of the specimen against and still clear the gages. The back-up plate was bolted to a supporting structure. To align the surface of the back-up plate with the cutter, a light cut was made with the Versa-Mil in position. The entire assembly was bolted to the floor by use of the laboratory floor pad eyes.

In the initial concept it was intended to hold the specimen with clamps at its edges to align the reinforcement against the back-up plate and mill the reinforcement with one set up. The assumption was made that the initial reinforcement would be accurate and could be used as the base for succeeding cuts. This was found to be a satisfactory assumption. However, through a misunderstanding by the authors about the Versa-Mil it was discovered that there was insufficient vertical travel. It was possible to rectify this oversight and obtain, as experience proved, a better method of attachment by milling first half way around and then moving the plate. A bar strongback with a stud to the back-up plate, clamping the reinforcement to the back-up plate, could then be used as shown in Figure 33.

E. HANDLING

Handling of the specimens was accomplished by use of an overhead rail. The overhead rail was constructed of two 2 x 10 fir beams bolted together. To protect the fir from the trolley

roller a 1x1x1/8" angle was fastened to the upper edges. The rail was supported by an A-frame structure at each end of the span. See Figure 28. As seen in the figure the rail passes under the upper testing machine crosshead thus permitting the specimen to be rolled directly into position. Since the upper edge of the specimen needed to extend over the top of the rail in order for the specimen to clear the lower crosshead, the specimen was hung in the sling arrangement shown in Figure 34. The tilt resulting from this method of handling

Figure 34 - Sling arrangement for hoisting and loading plate into the testing machine. The hoisting mechanism is a reel-type bomb hoist. The bomb hoist wire runs to the overhead rail.

aided in passing the specimen into the testing machine. In transferring the specimen to the milling machine from the testing machine, the specimen was lowered by use of the sling to the floor and then supported by the lifting arrangement shown in Figure 31. Due to the overall dimensions of the specimen it is noted that the position of the rail was quite critical initially and clearances involved were in the order of $\frac{1}{4}$ to $\frac{1}{2}$ inch.

APPENDIX II

DETAILS OF INSTRUMENTATION

The SR-4 strain gage was used for all strain measurements. Three types were used as listed in the following table.

	Nominal Gage Length (Inches)	Minimum Trim Width (Inches)	Nominal Resistance (Ohms)
A-5-1	1/2	11/32	120
A-7	1/4	7/32	120
A-19	1/16	1/8	60

The A-5 strain gage was used in the plate proper clear of the reinforcement while the other two types were used where either space or strain gradient was controlling. The A-19 was not initially used because of the inexperience of the authors. It was found that as the corner radius became smaller the strain gradient became peaked and thus the A-19 was used. By this time the authors had gained practical experience in the application of SR-4 strain gages. The gages were applied in accordance with the procedure given in Appendix III.

All readings were made with a Baldwin-Lima-Hamilton SR-4 type N Portable Strain Indicator, see Figure 35. This instrument was connected to the SR-4 gages by means of the following equipment:

(1) 20 channel Baldwin-Lima-Hamilton switching unit.

Figure 35a

Figure 35b

Figure 35 - Strain gage switching and reading station. Reading from left to right: strain indicator type N, 20 channel switching and balancing unit, toggle switch box, and (Figure 35a) 50 channel strain scanner or (Figure 35b) 24 channel DTMB switching unit.

(2) 50 channel Baldwin SR-4 Strain Scanner.

(3) 24 channel David Taylor Model Basin switching unit.

(4) 10 ON and OFF toggle switches.

The 20 channel switching and balancing unit and the 50 channel strain scanner units were basically the same. Each gage was connected to a channel with a corresponding dummy, a common dummy being used for each gage type. By use of a variable resistor on each channel it was possible to zero all gages to the same initial meter reading. Because of the low values of strain being read, the strain scanner recorder mechanism was not accurate enough and therefore the strain scanner was used as a switching and balancing unit only.

The 24 channel David Taylor Model Basin switch box provided for selection only of the gage to be used. The three units were mainly used for their switching capacity and thus the unit used on any particular specimen was a matter of availability of the unit. Number 20 solid insulated copper wire was used for all wiring.

Milling operations took their toll in strain gages. The largest single accident loss was caused by the SR-4 cable becoming wound on the milling cutter. The first specimen to be milled was #4 and the gages inside the opening on the reinforcement had their wires led to a center ring. It had been hoped that by tying the wires to the ring they could be held

clear of the milling cutter. All it took to tear off the leads of 21 gages was the lead from one gage being caught by the cutter. In succeeding specimens a thin plywood board was glued into the opening and the wires from the gages taped to this board. This solved the problem by being more positive in positioning the wires and even if a wire was touched it was milled rather than caught in the cutter.

The remaining losses during milling operations were either the result of a lead-off wire being milled off or heat burning the gages. The solution here was patience. Patience in positioning the gages during application and patience in milling to reduce the heat resulting from the cutting. In regards to the latter it was found the biggest aid was to use a freshly sharpened milling cutter. Feed, revolutions per minute, and cooling fluid had minor effects. It was only during the final cut when 50% of the metal being milled was weld material that heat was a problem, and it is the opinion of the authors that the hardness of this weld material was the offender.

On the first few specimens beeswax was used to waterproof the gages against humidity. During the milling operation the hot chips would bury themselves into the beeswax and elimination of wiring shorts was standard practice after milling. Elimination of the beeswax had no ill effects on the circuit properties.

APPENDIX III

PROCEDURAL DETAILS

A. <u>PROCEDURE FOR INSTALLATION OF SR-4 STRAIN GAGES*</u>

1. LOCATE. Scribe two perpendicular centerlines which intersect at the exact desired gage center and which are aligned with the desired gage orientation. The lines are extended clear of area to be subsequently prepared.

2. PREPARE THE SURFACE. All specimens were sand blasted to remove scale and paints prior to step 1. Gage locations are polished with emery paper mounted on a power disk to remove pits and rust collected since sand blasting. Surface is wiped clean with dry cotton.

3. RE-SCRIBE CENTERLINES. The centerlines are re-scribed lightly and the area repolished by hand with emery paper to remove any burrs which may have been formed.

4. CLEAN THE SURFACE. The surface is cleaned with acetone using clean swabs of cotton until cotton shows no discoloration. Polish with fresh dry swab of cotton.

5. STRAIN GAGE CHECK. Check the gage for proper electrical resistance after folding leads perpendicular to the gage so that it may be handled without touching the gluing surface.

6. APPLY THE GAGE. Gages were bonded with Duco household cement. Discard the initial drop of cement ejected from

---

* Taken from memorandum on "Procedure for Installing wire Resistance Strain Gages" by Edward Wenk, Jr., DTMB, August 1949.

a tube and avoid getting any hard material onto the gage. Apply a heavy line of cement along the perpendicular axis of the gage onto the gluing surface of the gage. Immediately mount the gage at its desired location properly aligned with the scribe marks. Using the finger tips, adhere the gage with an even pressure, work out from the center of the gage all excess cement and all air bubbles. Using the eraser end of a pencil work out those areas which still require it, i.e. adjacent to the gage leads. After wiping off excess cement, a sheet of paper is placed under a pound weight on the gage for three to five minutes. Where weights can not be placed the gage is held by the eraser end of a pencil for about one minute. After removing the weight and paper protector the entire gage is covered with a thin coat of cement extending beyond the edge of the gage at least 1/8 inch. Allow the gage to air dry for 24 hours.

7. RECHECK THE GAGE. Check the gage for proper gage resistance and adequate insulation from ground.

8. CONNECT THE GAGE ELECTRICALLY. Connect the electrical gage cable to the gage leads, one lead to the common and the other to the appropriate cable wire. Connections are made by twisting the bared wires together and soldering with resin core solder. A short length of flexible tubular insulation is adjusted over the bare joint and lead.

9. BAKE THE GAGE. All gages are baked about eight hours at 140°F using infra-red lamps.

10. WATERPROOF THE GAGE. Immediately after baking a light coat of beeswax is applied to the gage and connections extending about 1/2 inch beyond the edge of the cement.

11. RECHECK THE GAGE. Each gage is rechecked for continuity and a resistance to ground of 100 megs or more.

B. TEST PROCEDURE

Each specimen is subject to six tests between each of which is a milling operation. The following is the procedure for one test cycle.

1. Set up in testing machine.

a. Plate moved into testing machine by means of handling gear and upper pins inserted.

b. Lower coupling strongback made up to lower specimen strongback.

c. Adjustment of clevises to

(1) Obtain loading in the plane of the specimen. This is checked by plumbing the plate from upper to lower specimen strongbacks front and back at the plate edges.

(2) Obtain symmetrical loading in the specimen. This is checked by obtaining the axial strain below each of the upper clevises

by means of backed up strain gages located there. Adjustments are made by taking up or letting out on the appropriate coupling nut.

2. Test run.

a. When balancing equipment is available the gages are adjusted to the same initial reading.

b. Strain readings are obtained at standard load increments. (In most cases non-linearity was observed up to machine loads of 40,000 pounds. Therefore most tests were conducted between machine loads of 40,000 and 90,000 pounds.) Readings are obtained either by

(1) Method 1 - Vary the machine load at constant rate between the limits of the load. On each cycle of loading, the strain readings for a new gage location are obtained at designated loads.

(2) Method 2 - While holding the machine load at desired levels, strain readings for all gages are taken.

3. Transfer of plate between testing maching and milling jig.

a. Remove lower coupling strongback.

b. Support weight of plate on lower machine crosshead and remove upper pins.

c. Secure handling sling and pivot bracket to plate.

d. Transfer weight of plate to sling and roll plate out of the testing machine by means of overhead rail.

e. Lower plate to floor and transfer weight to upper lifting arrangement.

f. Roll plate into milling jig, and secure in position.

(1) Support weight from overhead rail.

(2) Clamp reinforcement with strongback.

(3) Clamp, wedge, and block and tackle as necessary to align reinforcement against back-up plate.

4. Milling. The milling operation consists of reducing the reinforcement height by 1/4 inch on each side of the plate per test. This is accomplished in four steps using a $1\frac{1}{2}$ to $2\frac{1}{2}$ inch shell cutter. The milling procedure is:

a. Mill upper half of reinforcement on back side.

b. Mill lower half of reinforcement on back side after raising the plate in the jig and reclamping.

c. Remove plate from milling jig, turn the plate around and reclamp in position.

5. Transfer the plate from the milling jig to the testing machine. Repeat step 3 in reverse and repeat the procedural cycle.

C. <u>TRANSFER OF SPECIMEN STRONGBACKS</u>

After completion of all tests the plate is transferred to the welding shop where

1. Specimen strongbacks are removed from completed plate by burning the specimen plate close to the weld between the specimen and the specimen strongback.

2. Specimen strongback is placed in Cincinnati milling machine and old weld milled off exposing the $\frac{1}{4}''$ x $\frac{1}{4}''$ groove.

3. New specimen is positioned in the $\frac{1}{4}$ x $\frac{1}{4}$ inch groove in the specimen strongback. The groove provides a snug fit between the two members.

4. The specimen and specimen strongback are arc-welded together by step welding.

APPENDIX IV

DERIVATIONS OF FORMULA AND SAMPLE CALCULATIONS

A. DETERMINATION OF STRAIN CONCENTRATION FACTORS

Figure 36 shows examples of the load-strain curves obtained from the actual test readings. The strain concentration factor multipliers were used to calculate the strain concentration factors from the slopes of the load-strain curves. The multipliers were derived as follows:

$$S = \frac{P}{A} = Ee$$

by rearranging

$$\frac{e}{P} = \frac{1}{AE} = \frac{1}{E \times t \times \text{WIDTH OF PLATING}}$$

$$\text{OR} \qquad \frac{et}{P} = \frac{1}{E \times \text{WIDTH OF PLATING}}$$

On the basis that E × width of the plating is the same for all the specimens, then the ratio et/P at infinity for specimen #n equals the ratio et/P for specimen #7:

$$\left(\frac{e_\ell t}{P}\right)_n = \left(\frac{e_\ell}{P}\right)_n t_n = \left(\frac{e}{P}\right)_7 t_7$$

The strain concentration factor is the ratio of the strain at a point to the strain at infinity. Expressed as an equation:

$$k = \frac{e}{e_\ell} = \frac{e/P}{e_\ell/P}$$

Thus, for specimen #n

$$k = \frac{(e/P)_n}{(e/P)_7 (t_7/t_n)} = \frac{t_n}{(e/P)_7 t_7} (e/P)_n$$

But e/P is the slope of the load-strain curve, thus

$$k = \left[\frac{t_n}{t_7 \ \text{SLOPE}_7}\right] \text{SLOPE}_n$$

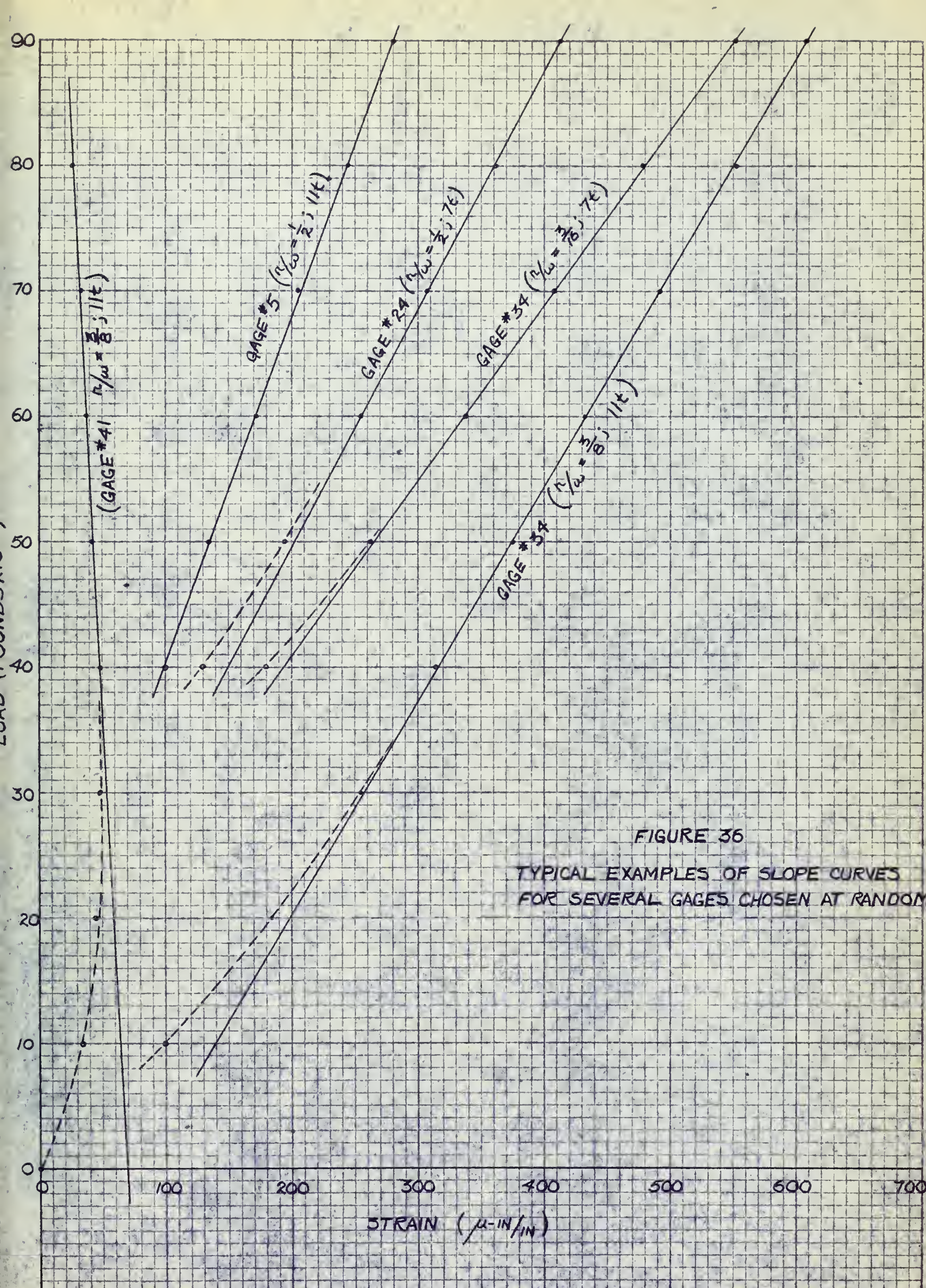


FIGURE 36

TYPICAL EXAMPLES OF SLOPE CURVES FOR SEVERAL GAGES CHOSEN AT RANDOM

B. TRANSVERSE SENSITIVITY

The derivations included here are based on the discussion and formulas in reference (9) on transverse sensitivity of SR-4 strain gages. Equation and page numbers refer to those used in the reference.

Equation 44, page 70 is one form of the relationship between the unit change in resistance and the Gage Factor, the Transverse Sensitivity Factor, and the strain parallel and normal to the gage axis. By a rearrangement of terms, and using the symbols of this investigation, equation 44 can be written as:

$$e_a' = \frac{1}{1-0.285K}(e_a + Ke_b)$$

$$e_b' = \frac{1}{1-0.285K}(e_b + Ke_a)$$

By combining the above two equations and solving for e_a in terms of the measured strains,

$$e_a = \frac{1-0.285K}{1-K^2}(e_a' - Ke_b')$$

Dividing by the strain at infinity an equation in terms of strain concentration factors is obtained:

$$k_a = \frac{e_a}{e_i} = \frac{1-0.285K}{1-K^2}(k_a' - Kk_b')$$

Using the experimental values for K given on page 65, the actual strain concentration factor corrected for transverse sensitivity is:

For A-5 gages K = 0.035

$$k_a = 0.99(k_a' - 0.035\,k_b')$$

For A-7 gages K = -0.010

$$k_a = k_a' + 0.01\,k_b'$$

To determine the effects of the transverse sensitivity of the gages on the results, trials were made using the data for representative ratios of e_x to e_y.

Example: For A-5 gages orientated in the direction of the applied load:

$$\frac{e_x'}{e_Y'} = -\frac{1}{3}$$

Therefore $$k_Y = 0.99\left[k_Y' - 0.035\left(-\tfrac{1}{3}\right)k_Y'\right]$$

$$k_Y = 1.002\,k_Y'$$

A formula for calculating a corrected stress value can be determined by substituting the strain equations above in

$$S_a = \frac{E}{1-u^2}(e_a + u e_b)$$

which results in

$$S_a = \frac{E}{1-u^2}\left(\frac{1-0.285\,K}{1-K^2}\right)\left[e_a'(1-uK) + e_b'(u-K)\right]$$

C. <u>THEORETICAL REINFORCED CIRCULAR OPENING</u>

The following calculations are based on the work of Reissner and Morduchow (10) on reinforced circular cutouts in plane sheets. The symbols and equation numbers used in the following calculations are the same as those used in reference (10) except as noted.

The strain perpendicular to the radius, expressed in polar coordinates, at any point is:

$$\epsilon_\phi = \frac{1}{E_s}(\sigma_\phi - \nu\sigma_r)$$

$$\frac{\epsilon_\phi E_s}{\sigma_o} = \frac{\sigma_\phi}{\sigma_o} - \frac{\nu\sigma_r}{\sigma_o}$$

but $\frac{\epsilon_\phi E_s}{\sigma_o}$ = the concentration factor

therefore, concentration factor $= \frac{\sigma_\phi}{\sigma_o} - \frac{\nu\sigma_r}{\sigma_o}$

But σ_ϕ and σ_r are found by adding the constraint stress distribution from equations 24 to the original stress distribution, equations 19. By substituting the values of σ_ϕ and σ_r into the above concentration factor equation, the transverse concentration factor distribution along the face of the reinforcement can be expressed as:

$$\text{Concentration factor} = 0.35 - 1.48\frac{K_{30}}{\sigma_o} + \left[0.65 + 10.10\frac{K_{22}}{\sigma_o} + 1.37\frac{K_{42}}{\sigma_o}\right]\cos 2\phi$$

Now K_{30}, K_{22}, and K_{42} are determined from equations 23 where:

A_r = 0.250×(reinforcement height) inches^2

a = 3.875"

a_1 = 4.000"

d = 0.250"

$E_r = E_s$

$I_r = \frac{1}{12}d^3$(reinforcement height) inches^4

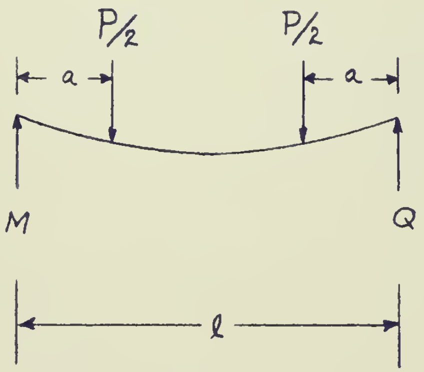
r = 3.75"

t = 0.230"

ν = 0.3

D. DESIGN OF SPECIMEN STRONGBACK

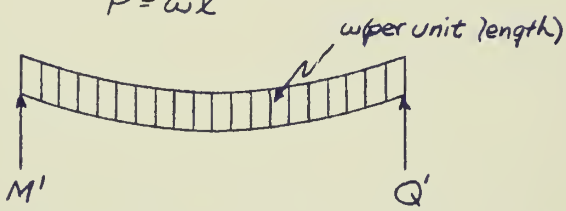
The specimen strongback was designed by considering it as a beam carrying a uniform load and simply supported at two points. The length of the beam is 40 inches with supports 9 inches from each end. The total load was equal to P. The principle of superposition was used for the solution.



THE MAXIMUM DEFLECTION OCCURS AT $l/2$

$$d_{(l/2)} = \frac{Pa\,(3l^2 - 4a^2)}{48EI}$$

$P = \omega l$



$$d_{(l/2)} = \frac{5Pl^3}{348EI}$$

By using superposition in such a way that the reactions m & m' and q & q' cancel out then the beam will have the same deflection at m, q, and $l/2$ when: .

$$\frac{Pa\,(3l^2 - 4a^2)}{48EI} = \frac{5Pl^3}{348EI}$$

$$\frac{9\,[3(40)^2 - 4(9)^2]}{I} = \frac{5(40)^3}{I}$$

$$\frac{10{,}071}{I} \approx \frac{10{,}000}{I} \qquad \text{FOR } I = I$$

This shows that the deflections at m, q, and $l/2$ will be equal regardless of the value of I.

APPENDIX V

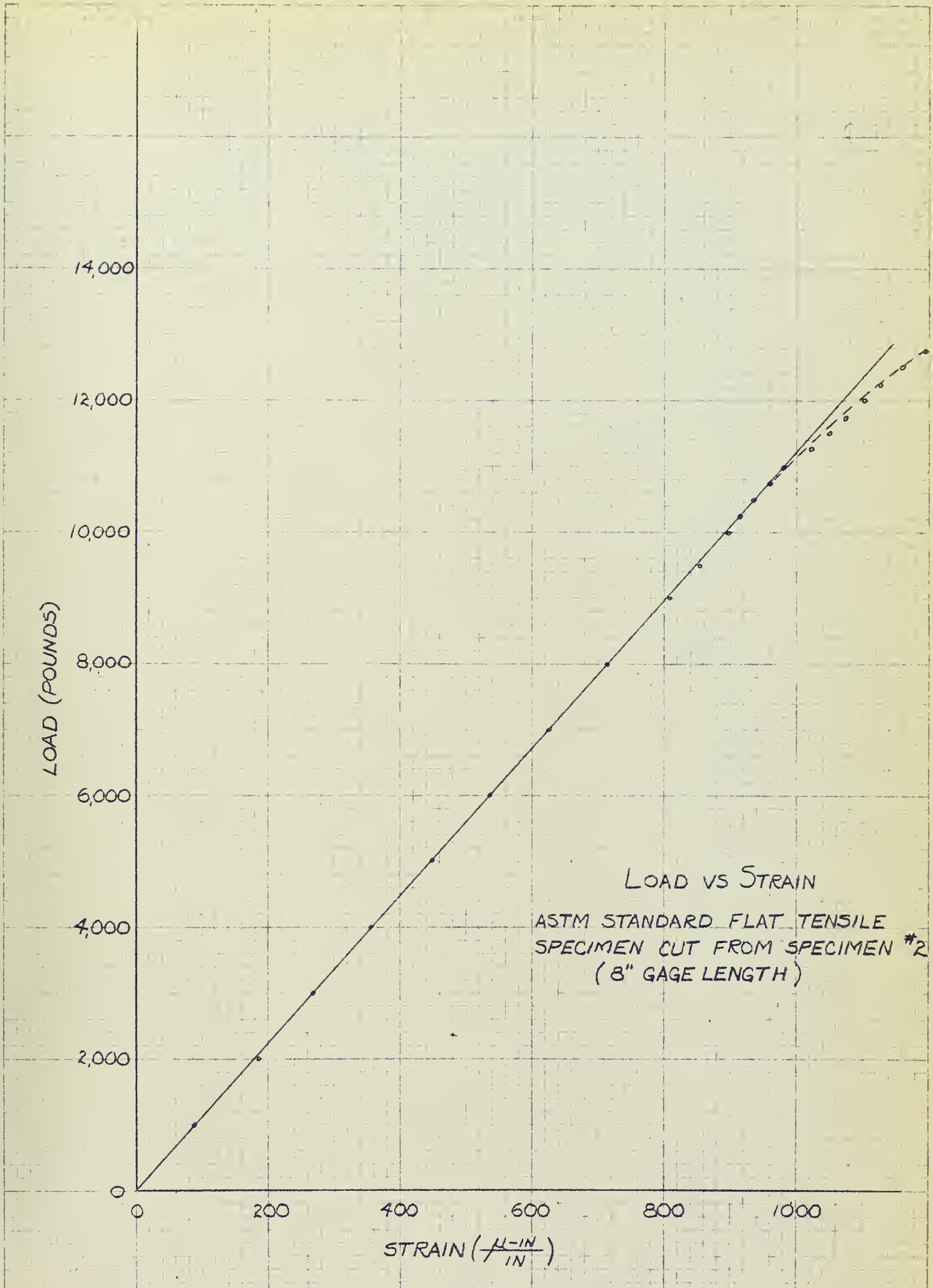
MODULUS OF ELASTICITY

A eight inch gage length ASTM standard flat tensile specimen cut from specimen #2 was tested to determine the tensile properties of the material used. The measured cross-sectional area of the test section was 0.374 inches^2. The modulus of elasticity was determined as follows:

$$S = \frac{P}{A} = Ee$$

$$\text{or} \quad E = \frac{1}{A} \times \frac{P}{e}$$

where P/e is the slope from Figure 37.

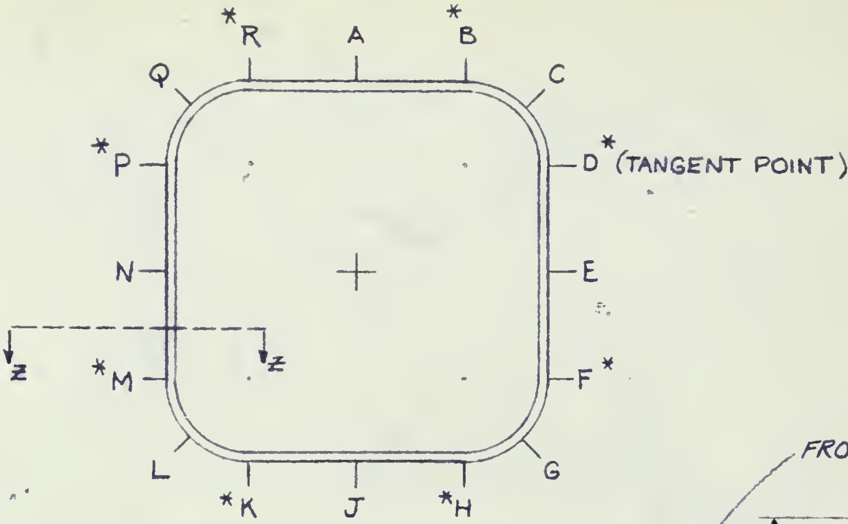


14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
LOAD (POUNDS)
0
200
400
600
800
1000
STRAIN ($\frac{\mu\text{-IN}}{\text{IN}}$)
LOAD VS STRAIN
ASTM STANDARD FLAT TENSILE
SPECIMEN CUT FROM SPECIMEN #2
(8" GAGE LENGTH)

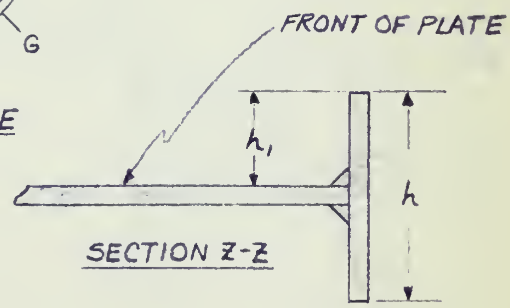
FIGURE 37

APPENDIX VI

ORIGINAL DATA SUMMARIES



REPRESENTATIVE PLATE



SECTION Z-Z

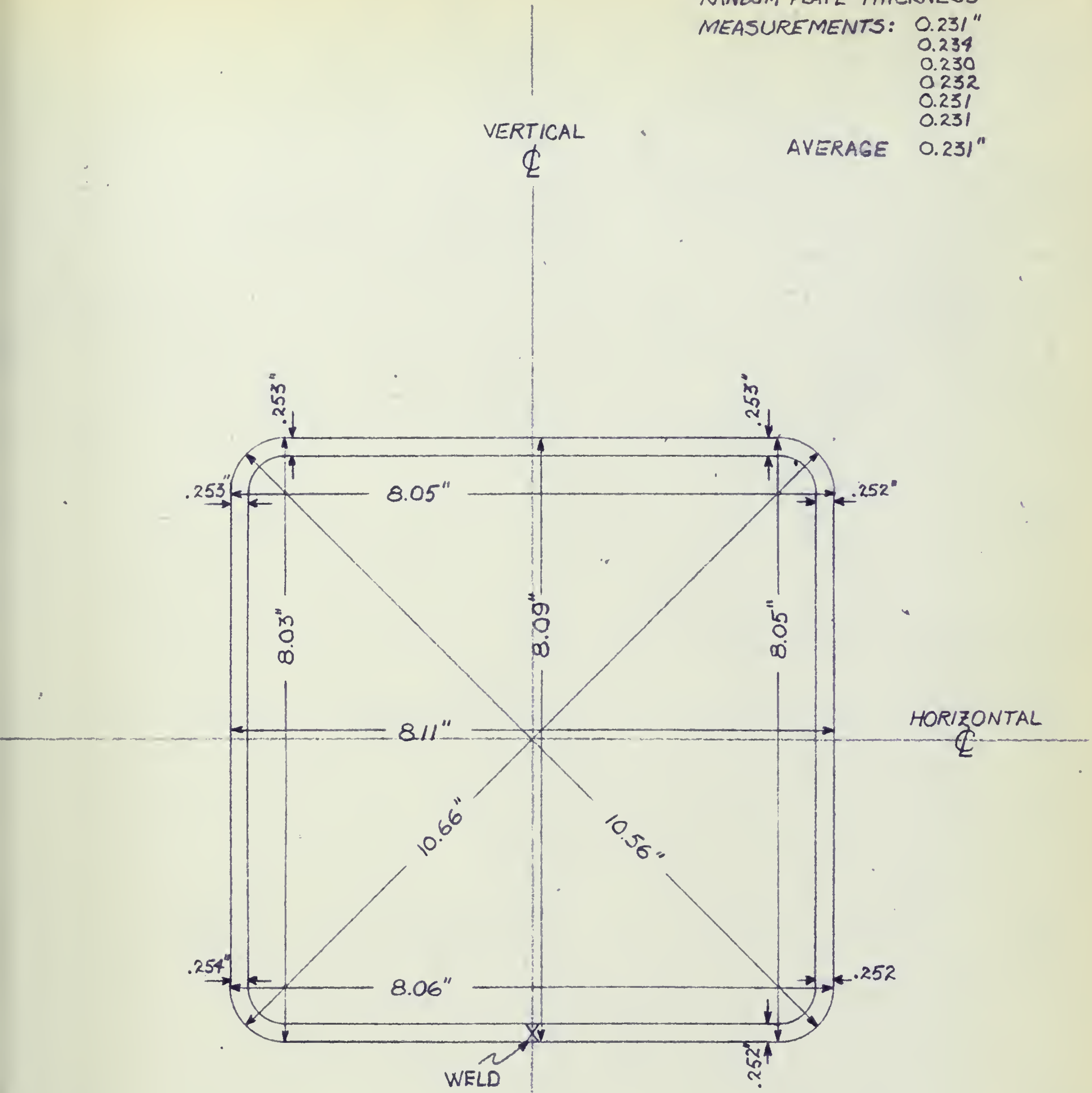
LOCATION	PLATE NUMBER 1	2	3	4	5	6
A	—	1.30"	1.25"	—	—	1.25"
B	1.27"	—	—	1.27"	1.28"	—
C	—	1.30	1.25	—	—	1.25
D	1.25	1.30	—	—	1.27	—
E	—	1.30	1.25	—	—	1.22
F	1.23	1.30	—	—	1.23	—
G	—	—	1.25	—	—	1.22
H	1.22	1.31	—	—	1.22	—
J	—	—	1.22	—	—	1.25
K	1.22	1.31	—	1.27	1.25	—
L	—	—	1.25	—	—	1.22
M	1.23	1.34	—	—	1.25	—
N	—	1.31	—	—	—	1.22
P	1.27	1.30	—	—	1.22	—
Q	—	—	1.25	—	—	1.22
R	1.27	1.30	—	1.27	1.25	—

h_1 - VALUES

REINFORCEMENT

ORIGINAL LOCATION

RANDOM PLATE THICKNESS
MEASUREMENTS: 0.231"
0.234
0.230
0.232
0.231
0.231
AVERAGE 0.231"



ORIGINAL HT. OF REINFORCEMENT: 2.734" (UNIFORM)

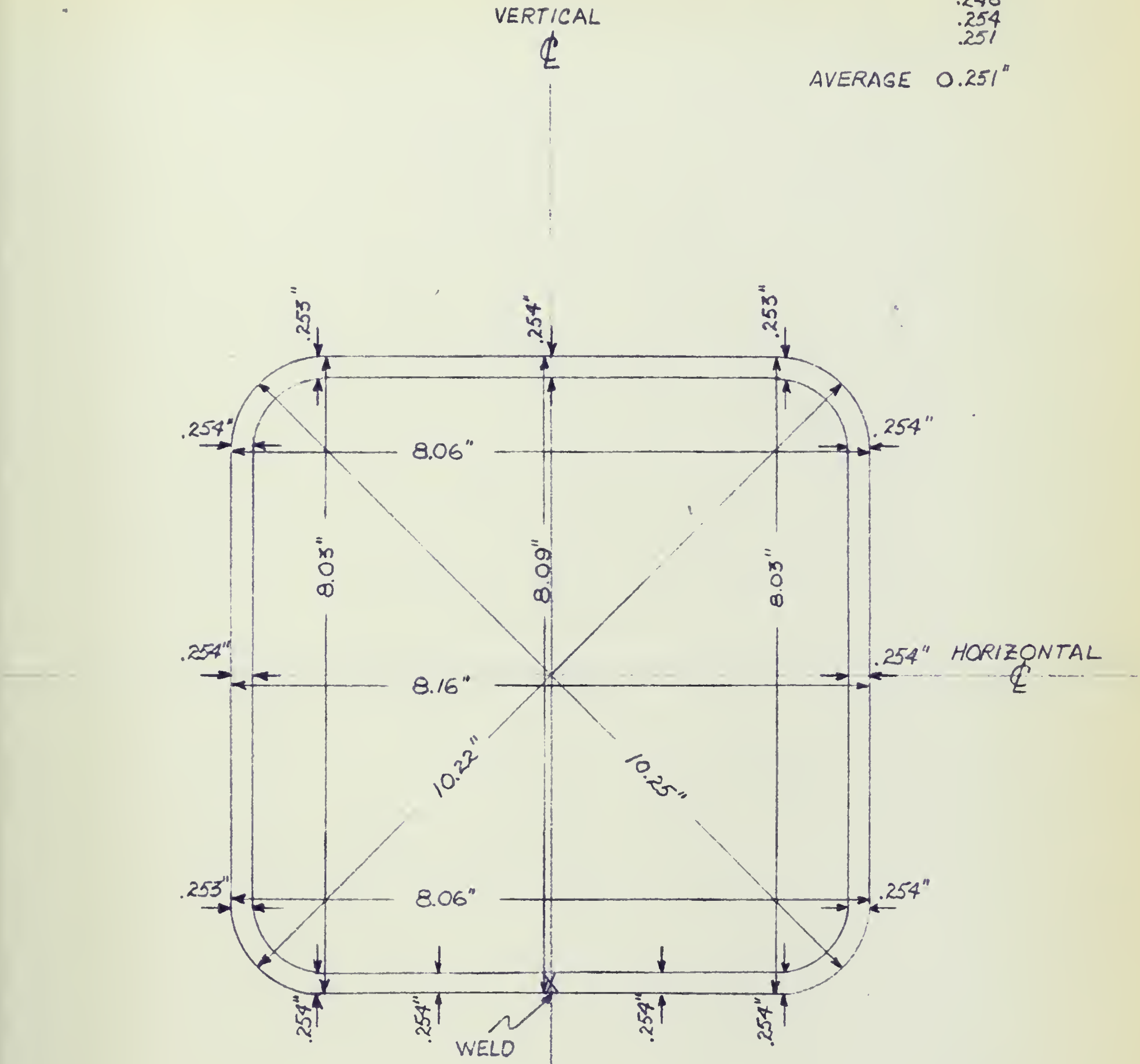
$r/\omega = \frac{1}{16}$.

PLATE # 1

ORIGINAL DIMENSIONS
SCALE ½" = 1"

RANDOM PLATE THICKNESS
MEASUREMENTS: 0.249"
.254
.251
.246
.254
.251

AVERAGE 0.251"



ORIGINAL HT. OF REINFORCEMENT: 2.734" (UNIFORM)

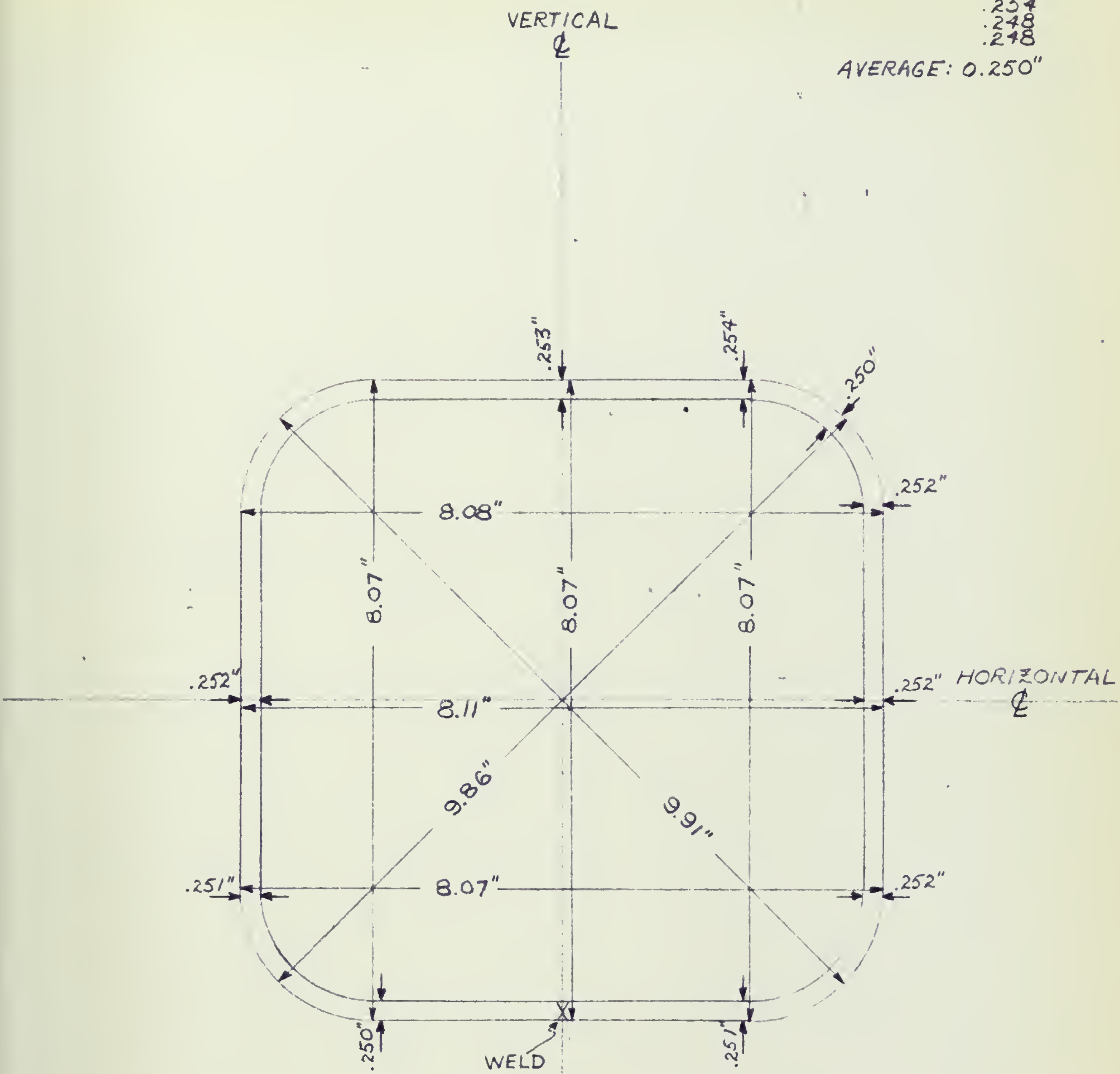
$r/w = \frac{1}{8}$

PLATE #2

ORIGINAL DIMENSIONS
SCALE ½" = 1"

RANDOM PLATE THICKNESS
MEASUREMENTS: 0.254"
.248
.248
.254
.248
.248

AVERAGE: 0.250"



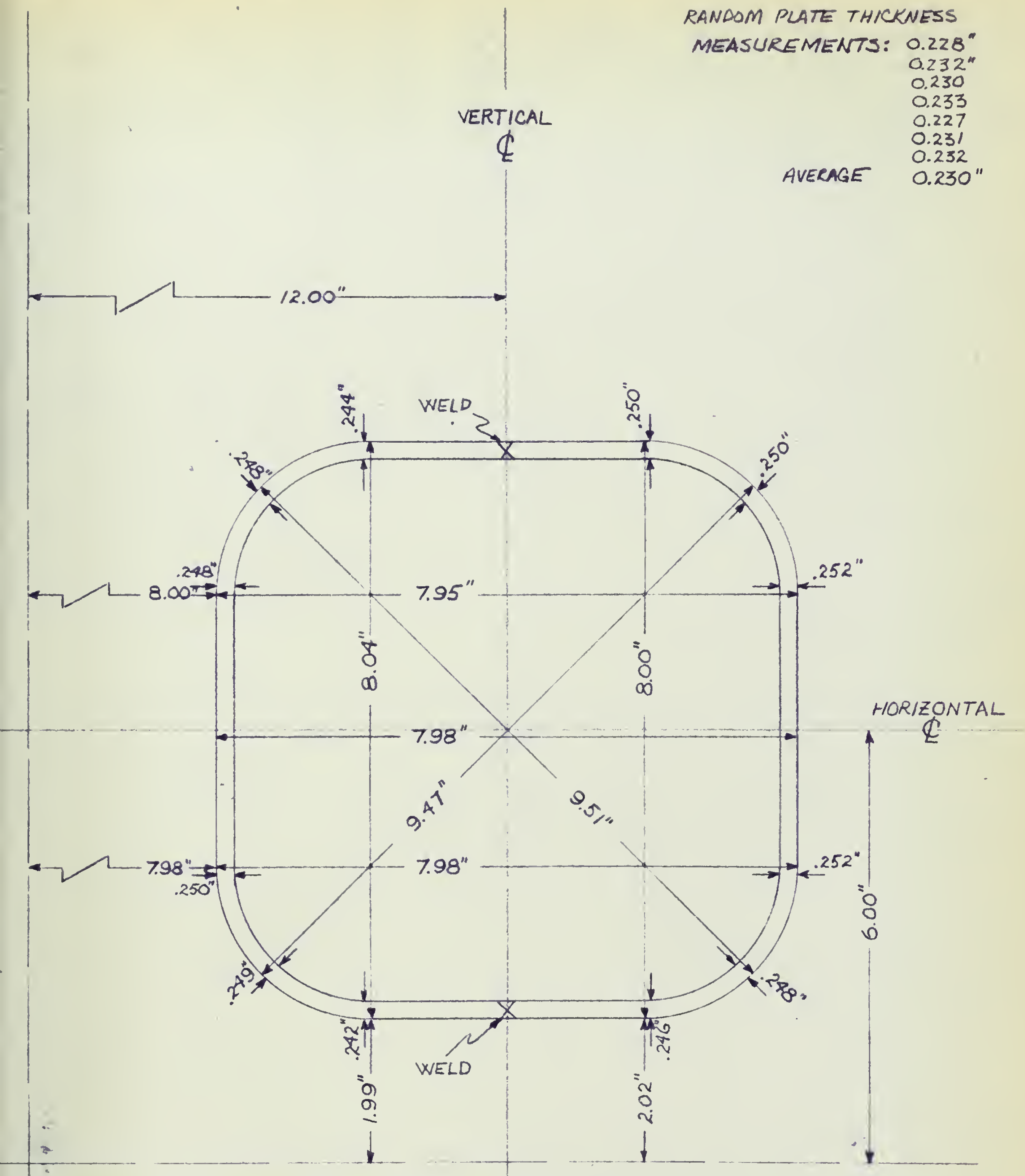
ORIGINAL HT. OF REINFORCEMENT 2.734" (UNIFORM)

$r/\omega = \frac{3}{16}$

PLATE # 3

ORIGINAL DIMENSIONS
SCALE ½" = 1"

RANDOM PLATE THICKNESS
MEASUREMENTS: 0.228"
0.232"
0.230
0.233
0.227
0.231
0.232
AVERAGE 0.230"



ORIGINAL HT. OF REINFORCEMENT: 2.734" (UNIFORM)

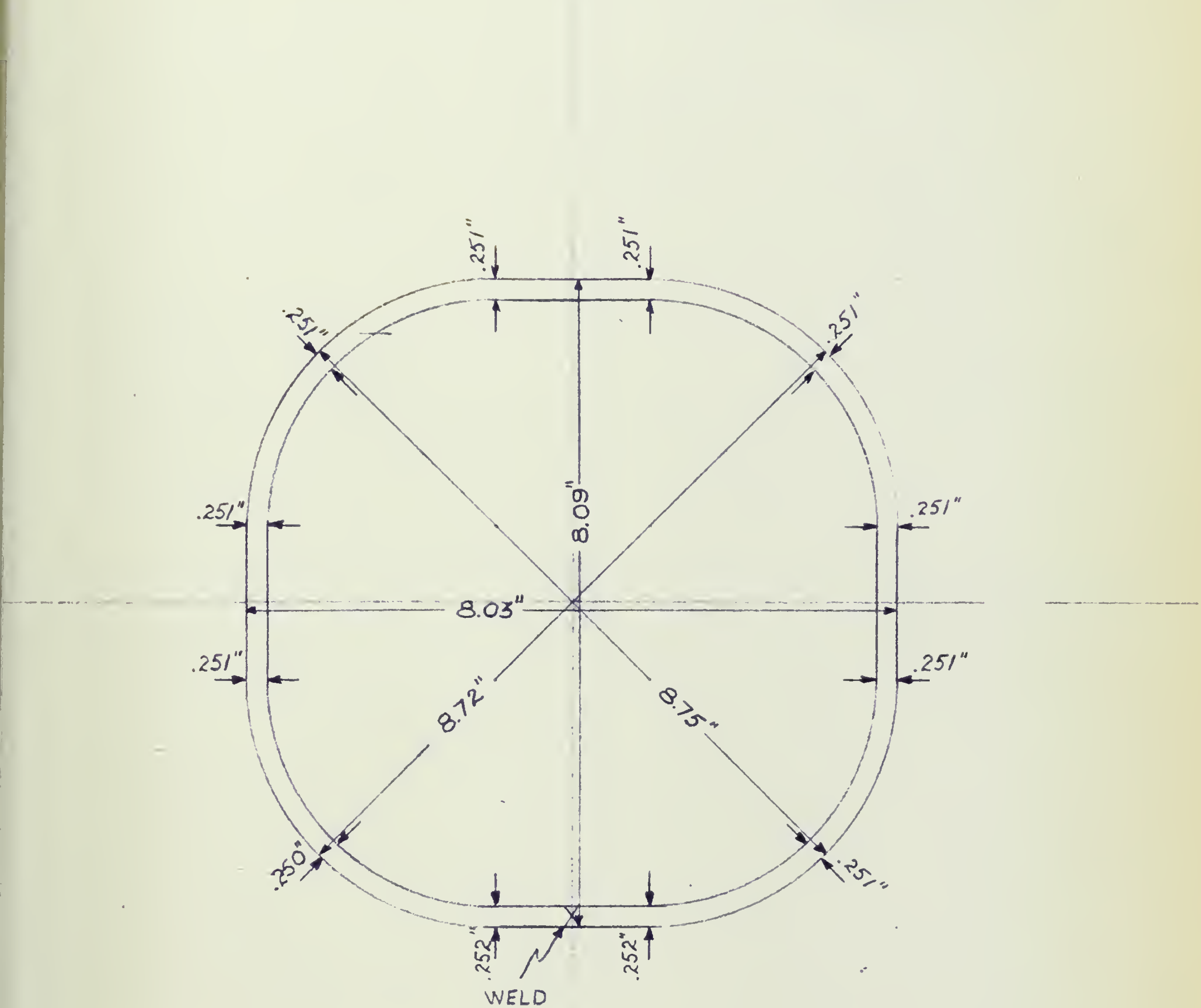
$r/\omega = \frac{1}{4}$

PLATE #4

ORIGINAL DIMENSIONS
SCALE 1/2" = 1"

RANDOM PLATE THICKNESS
MEASUREMENTS: 0.228"
.232"
.227"
.232"
.234"
AVERAGE: 0.231"

VERTICAL
℄



ORIGINAL HT. OF REINFORCEMENT: 2.734" (UNIFORM)

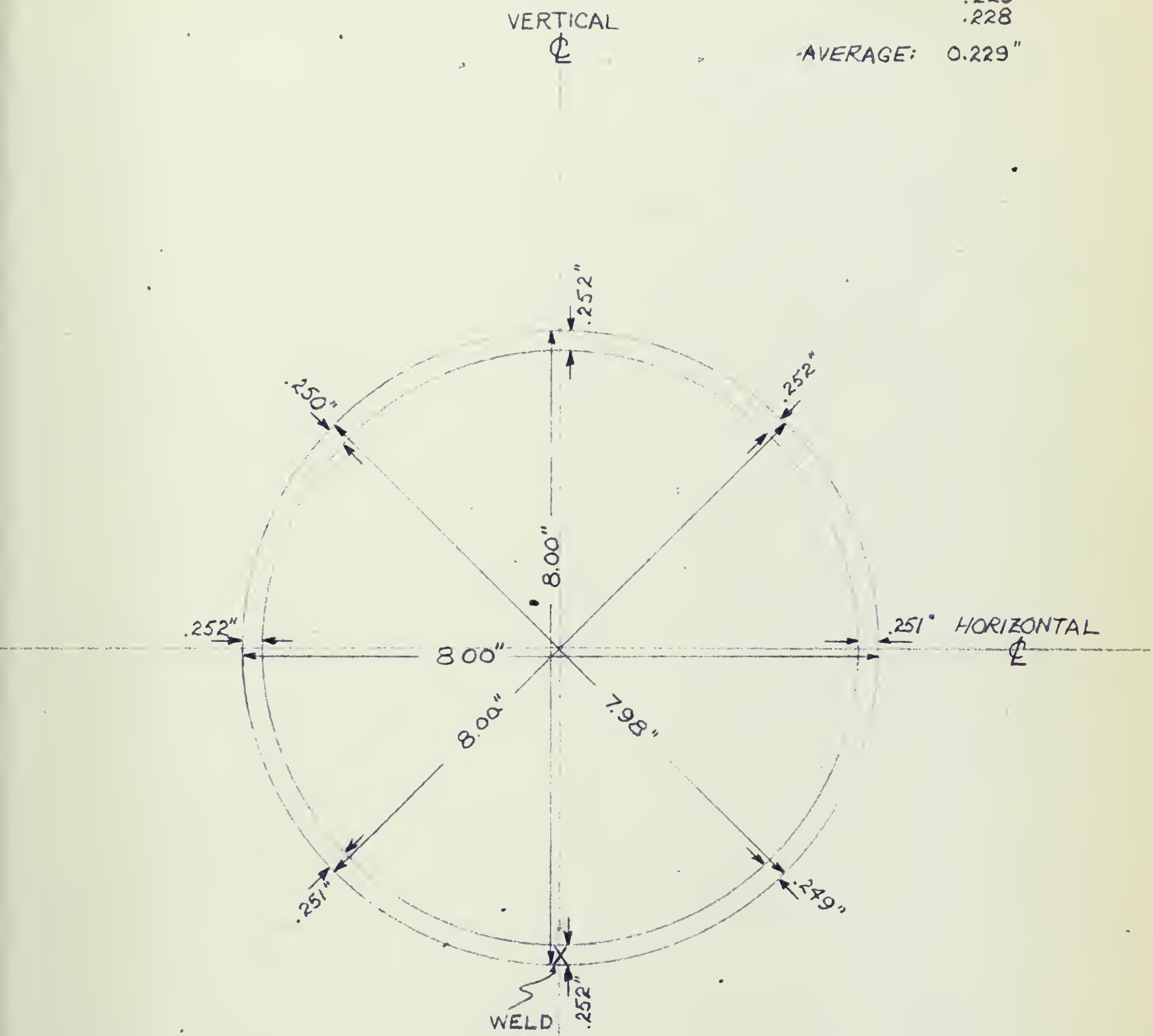
$r/\omega = \frac{3}{8}$

PLATE #5

ORIGINAL DIMENSIONS
SCALE ½" = 1"

RANDOM PLATE THICKNESS
MEASUREMENTS: 0.229"
.232
.228
.232
.225
.228

AVERAGE: 0.229"



ORIGINAL HT. OF REINFORCEMENT: 2.734" (UNIFORM)

$r/w = \frac{1}{2}$

PLATE #6

ORIGINAL DIMENSIONS
SCALE 1/2" = 1"

θ-VALUES FOR STRAIN GAGES ALONG OPENING BOUNDARY

PLATE #1 $r/\omega = \frac{1}{16}$		PLATE #2 $r/\omega = \frac{1}{8}$		PLATE #3 $r/\omega = \frac{3}{16}$		PLATE #4 $r/\omega = \frac{1}{4}$		PLATE #5 $r/\omega = \frac{3}{8}$		PLATE #6 $r/\omega = \frac{1}{2}$	
GAGE NO.	θ°	GAGE NO.	θ°	GAGE NO.	θ°	GAGE NO.	θ°	GAGE NO.	θ°	GAGE NO.	θ°
18	02.3	33	0.0	35	359.0	55	01.0	36	0.0	35	359.0
17	21.3	32	20.5	34	31.5	54	15.5	35	13.0	34	16.0
16	34.5	31	36.5	33	217.8	56	30.0	34	30.0	22	29.5
47	218.8	30	220.0	32	43.0	52	43.5	33	45.0	32	45.0
46	132.0	29	44.5	31	231.2	45	60.0	32	75.5	31	59.0
12	224.4	28	230.0	30	57.5	53	75.0	31	90.0	16	74.5
11	44.7	27	53.0	29	73.8	51	90.0			29	90.0
10	226.6	26	90.0	28	90.0						
13	48.8										
6	54.5										
7	71.0										
8	89.4										

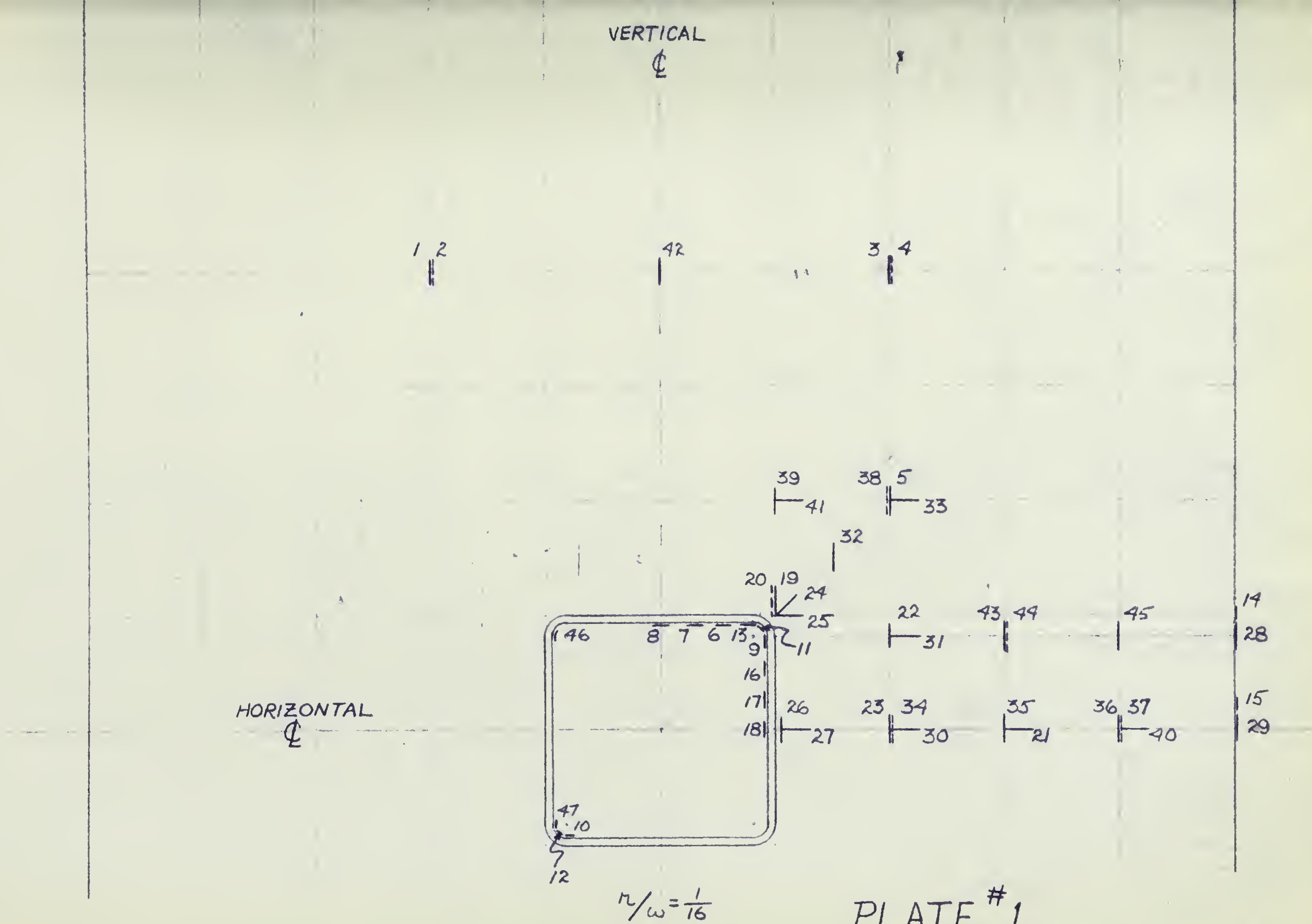


PLATE # 1
STRAIN GAGE LOCATION
SCALE 1/5" = 1"

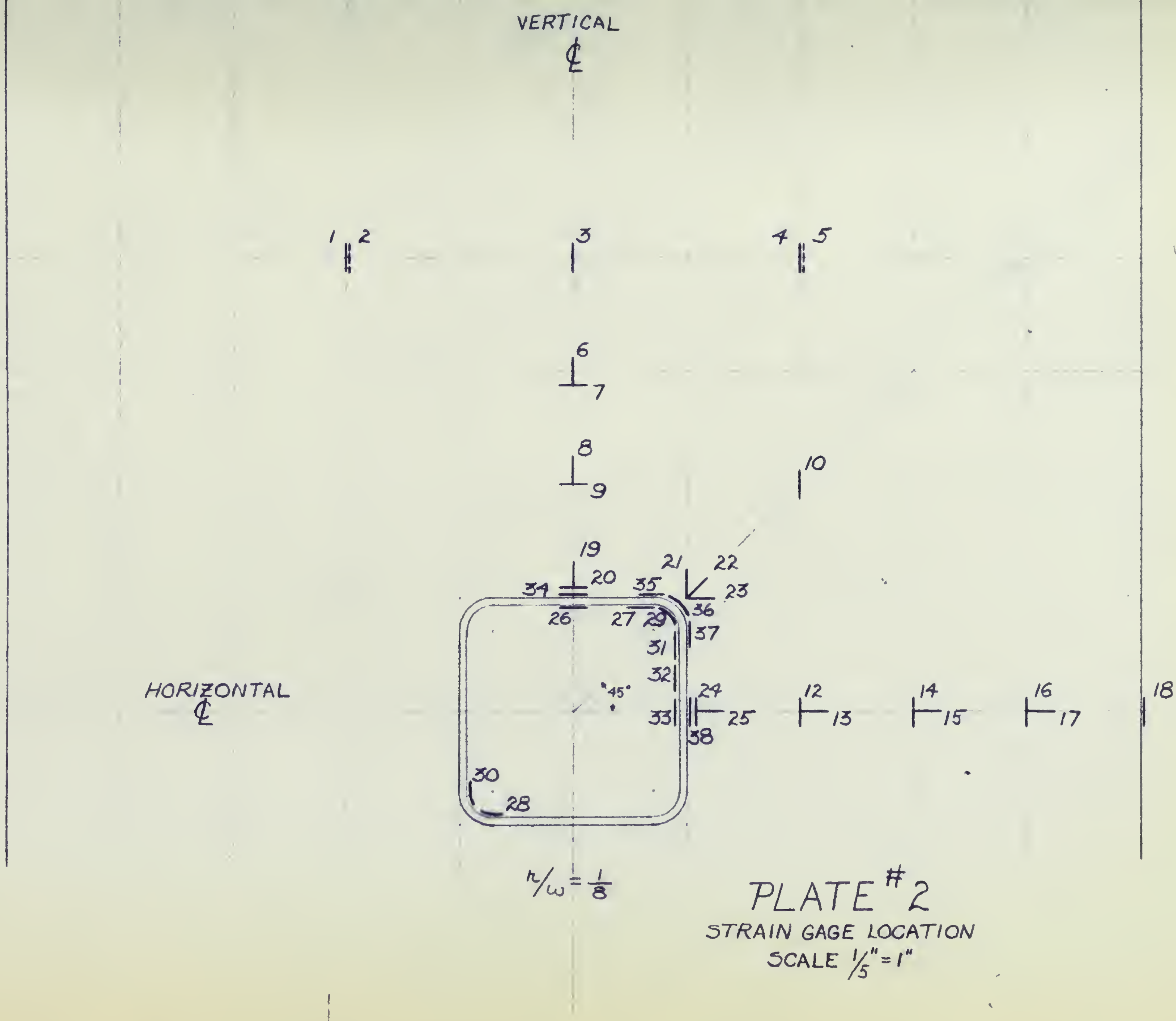


PLATE # 2
STRAIN GAGE LOCATION
SCALE 1/5" = 1"

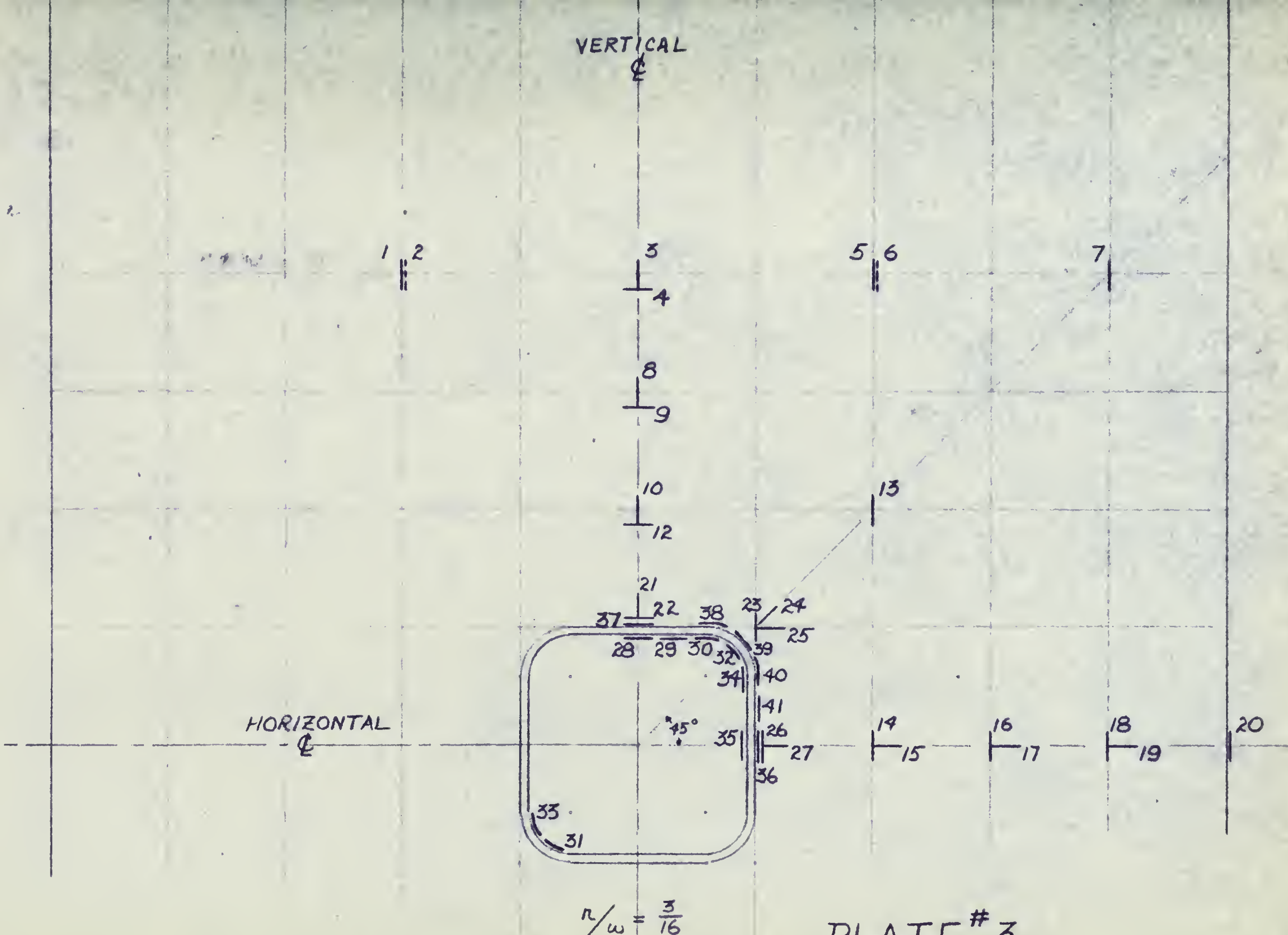
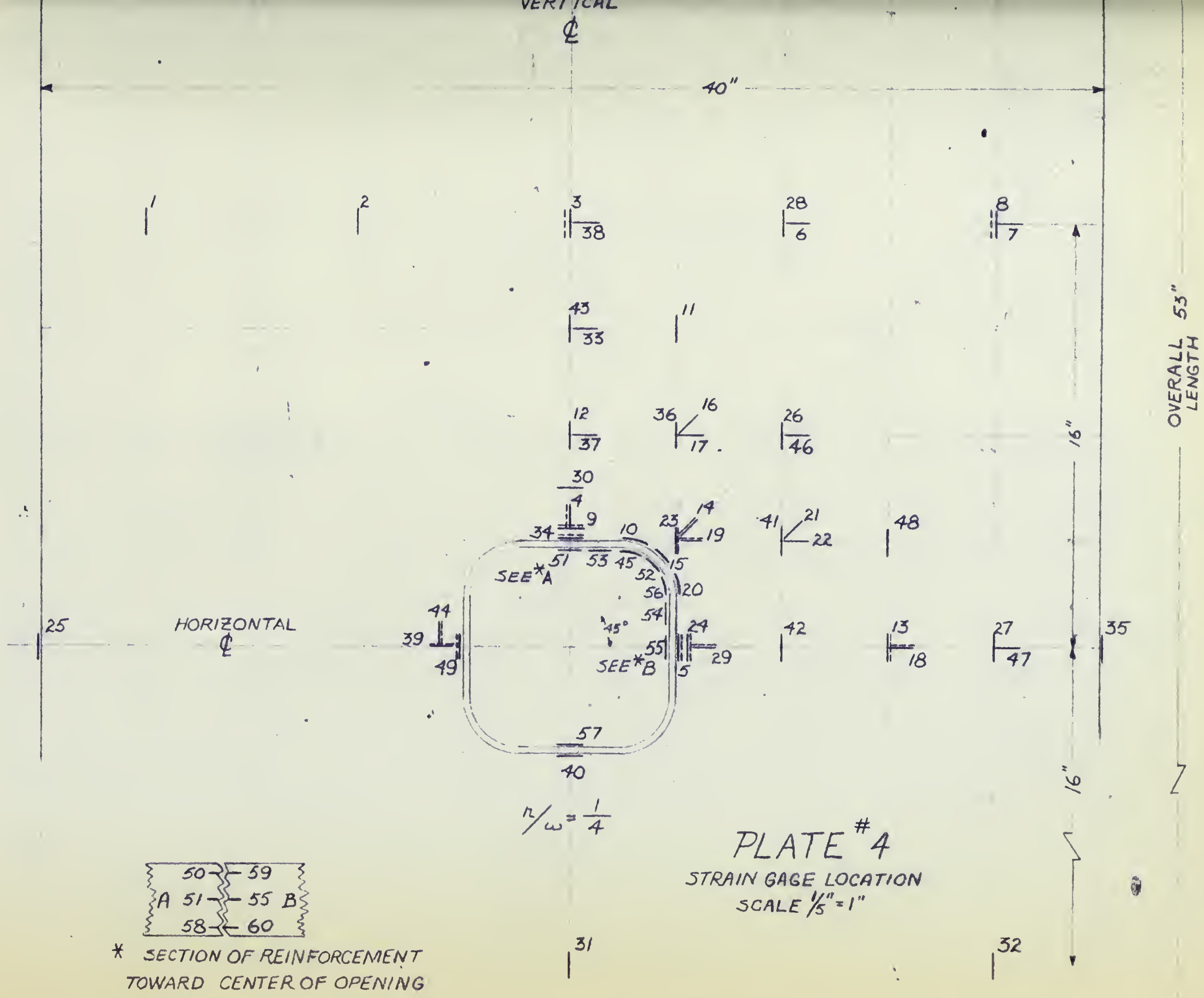
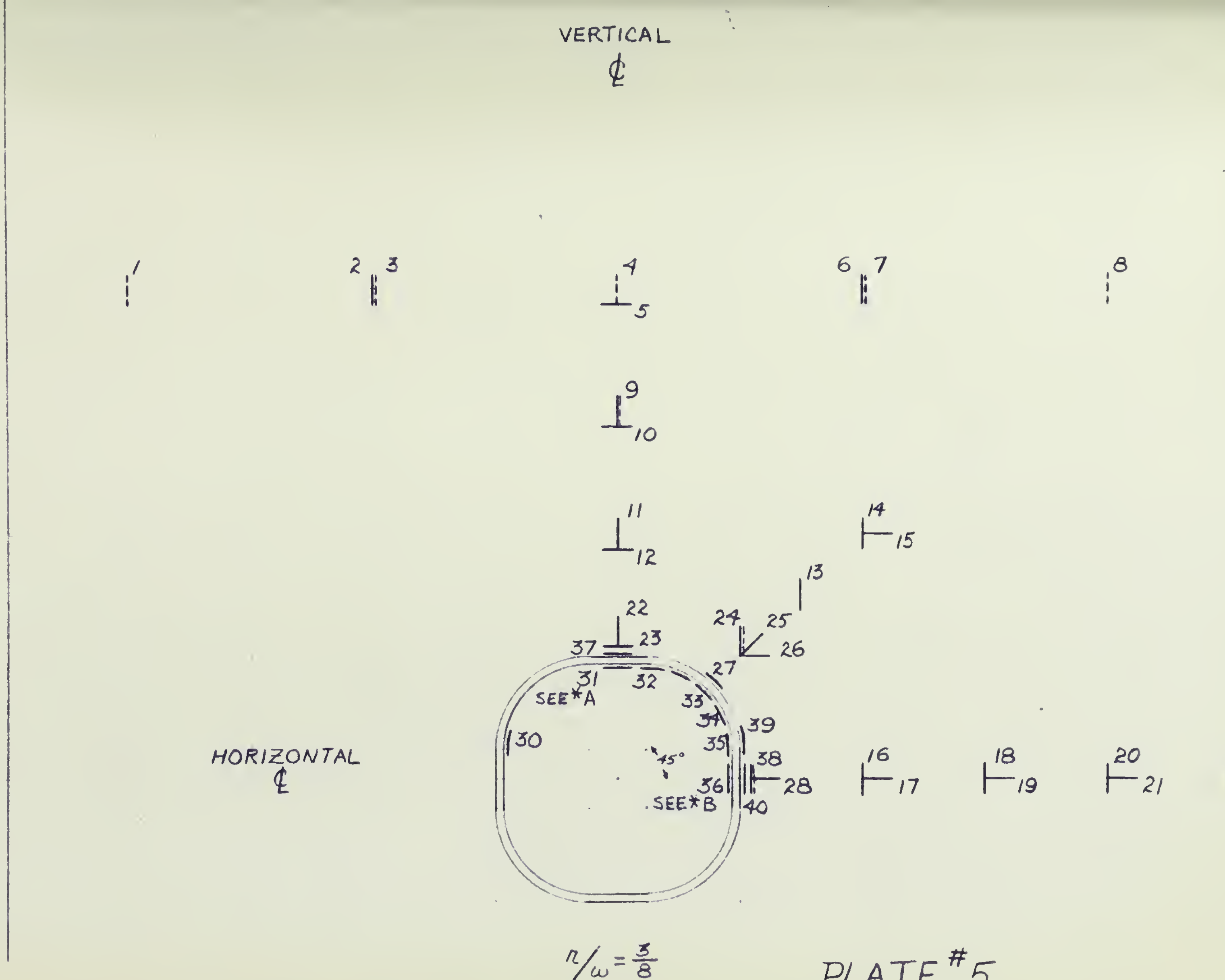


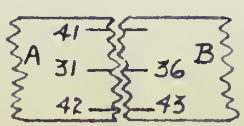
PLATE # 3

STRAIN GAGE LOCATION

SCALE 1/5" = 1"


VERTICAL ℄
40"
OVERALL LENGTH 53"
16"
16"
HORIZONTAL ℄
$r/\omega = \frac{1}{4}$
SEE*A
SEE*B
45°
PLATE # 4
STRAIN GAGE LOCATION
SCALE 1/5" = 1"
A 50 51 58
B 59 55 60
* SECTION OF REINFORCEMENT TOWARD CENTER OF OPENING

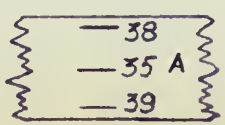




* SECTION OF REINFORCEMENT TOWARD CENTER OF OPENING

PLATE #5
STRAIN GAGE LOCATION
SCALE 1/5" = 1"

$r/\omega = \frac{1}{2}$



* SECTION OF REINFORCEMENT TOWARD CENTER OF OPENING

PLATE #6

STRAIN GAGE LOCATION

SCALE 1/5" = 1"

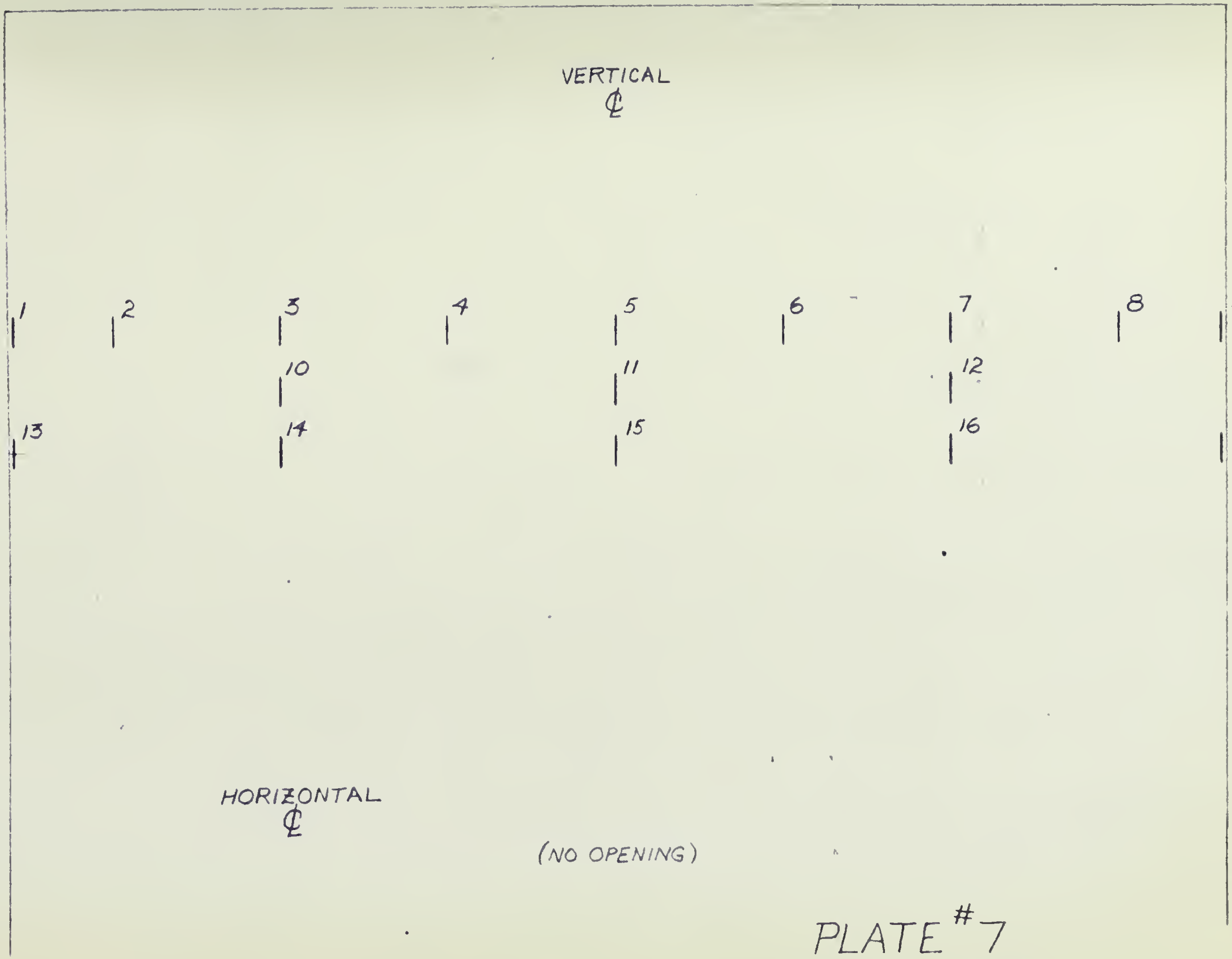


PLATE #7
STRAIN GAGE LOCATION
SCALE 1/5" = 1"

SUMMARY OF STRAIN CONCENTRATION MULTIPLIERS

Specimen	t	Multiplier
1	0.231	0.0514
2	0.251	0.0558
3	0.250	0.0556
4	0.230	0.0511
5	0.231	0.0513
6	0.229	0.0509
7	0.225	0.0500

Specimen #1

	1t slope	1t conc	3t slope	3t conc	5t slope	5t conc	7t slope	7t conc	9t slope	9t conc	11t slope	11t conc
1	18.1	0.93	17.5	0.90	17.9	0.92	17.8	0.91	18.2	0.94	17.9	0.92
2	20.2	1.04	20.3	1.04	20.6	1.06	20.0	1.03	19.5	1.00	20.2	1.04
3	16.2	0.83	16.7	0.86	16.9	0.87	17.0	0.87	17.5	0.90	17.0	0.87
4	20.8	1.07	20.7	1.06	20.7	1.06	20.6	1.06	20.1	1.03	20.7	1.06
5	26.4	1.36	25.8	1.33	24.4	1.25	24.5	1.26	24.3	1.25	24.0	1.23
6	-12.6	-0.65	-10.3	-0.53	-10.4	-0.54	- 9.5	-0.49	- 9.1	-0.47	- 8.6	-0.44
7	-15.6	-0.80	-10.8	-0.56	-10.3	-0.53	- 9.2	-0.47	- 8.4	-0.43	- 8.1	-0.42
8	-15.2	-0.78	-11.0	-0.57	-10.0	-0.52	- 9.0	-0.46	- 8.1	-0.42	- 7.8	-0.40
9	--	--	49.5	2.55	47.4	2.44	45.8	2.36	45.6	2.35	45.1	2.32
10	--	--	20.7	1.06	19.3	0.99	19.9	1.02	20.0	1.03	19.4	1.00
11	47.1	2.42	38.6	1.99	36.6	1.88	36.0	1.85	35.4	1.82	35.2	1.81
12	41.2	2.12	30.1	1.55	37.7	1.94	37.2	1.91	36.0	1.85	36.6	1.88
13	0.0	0.00	0.0	0.00	0.6	0.03	0.8	0.04	0.8	0.04	0.8	0.04
14	--	--	--	--	--	--	--	--	--	--	15.7	0.81
15	14.4	0.74	14.0	0.72	14.6	0.75	14.6	0.75	14.3	0.74	14.3	0.74
16	36.2	1.86	29.2	1.50	24.5	1.26	23.0	1.18	22.4	1.15	21.6	1.11
17	34.0	1.75	29.9	1.54	24.1	1.24	20.5	1.05	18.1	0.93	17.0	0.87
18	--	--	27.5	1.41	23.2	1.19	20.0	1.03	18.1	0.93	16.2	0.83
19	25.0	1.29	33.2	1.71	32.2	1.66	33.6	1.73	33.6	1.73	33.9	1.74
20	21.8	1.12	30.5	1.57	33.5	1.72	33.9	1.74	35.4	1.82	36.0	1.85
21	- 3.2	-0.16	- 3.7	-0.19	- 4.1	-0.21	- 4.5	-0.23	- 4.1	-0.21	- 4.4	-0.23
22	26.0	1.34	26.3	1.35	23.9	1.23	24.0	1.23	23.5	1.21	23.1	1.19
23	18.2	0.94	18.8	0.97	17.0	0.87	17.0	0.87	16.7	0.86	16.0	0.82
24	- 3.6	-0.19	- 3.0	-0.15	0.2	0.01	2.0	0.10	2.7	0.14	3.0	0.15
25	- 8.0	-0.41	-16.2	-0.83	-15.5	-0.80	-16.5	-0.85	-15.8	-0.81	-16.0	-0.82
26	28.0	1.44	29.3	1.51	23.4	1.20	20.7	1.06	19.0	0.98	17.3	0.89
27	- 7.4	-0.38	- 8.0	-0.41	- 5.8	-0.30	- 5.5	-0.28	- 4.7	-0.24	- 4.6	-0.24
28	16.6	0.85	17.2	0.88	17.3	0.89	17.3	0.89	17.2	0.88	17.0	0.87
29	15.4	0.79	15.8	0.81	16.1	0.83	16.5	0.85	16.3	0.84	16.3	0.84
30	- 5.0	-0.26	- 5.8	-0.30	- 5.5	-0.28	- 6.2	-0.32	- 6.0	-0.31	- 6.0	-0.31
31	- 4.4	-0.23	- 4.7	-0.24	- 3.5	-0.18	- 3.9	-0.20	- 3.5	-0.18	- 3.5	-0.18
32	27.2	1.40	26.0	1.34	25.5	1.31	25.5	1.31	24.5	1.26	24.0	1.23
33	- 7.2	-0.37	- 7.3	-0.38	-- 7.0	-0.36	- 6.4	-0.33	- 5.9	-0.30	- 5.6	-0.29
34	28.8	1.48	25.5	1.31	25.7	1.32	25.0	1.28	25.0	1.28	25.5	1.31
35	14.4	0.74	15.7	0.81	14.5	0.75	14.5	0.75	14.3	0.74	14.1	0.72
36	14.2	0.73	15.5	0.80	14.9	0.77	15.1	0.78	15.5	0.80	15.0	0.77
37	23.0	1.18	20.0	1.03	21.4	1.10	21.5	1.11	22.0	1.13	21.8	1.12
38	17.8	0.92	15.7	0.87	18.5	0.95	17.1	0.88	16.4	0.84	16.2	0.83
39	18.8	0.97	20.2	1.04	20.5	1.05	20.5	1.05	20.8	1.07	20.5	1.05
40	- 3.8	-0.20	- 4.5	-0.23	- 4.5	-0.23	- 4.4	-0.23	- 4.0	-0.21	- 4.1	-0.21
41	- 8.4	-0.43	-10.3	-0.53	- 9.1	-0.47	- 9.0	-0.46	- 8.8	-0.45	- 8.2	-0.42
42	13.2	0.68	12.0	0.62	13.5	0.69	13.8	0.71	13.7	0.70	13.7	0.70
43	23.0	1.18	23.5	1.21	21.8	1.12	21.7	1.12	21.6	1.11	21.6	1.11
44	17.8	0.92	15.2	0.78	16.9	0.87	16.6	0.85	16.1	0.83	16.1	0.83
45	20.4	1.05	22.7	1.17	20.6	1.06	20.5	1.05	20.4	1.05	20.3	1.04
46	73.4	3.78	57.3	2.95	53.2	2.74	--	--	--	--	--	--
47	13.7	0.70	16.6	0.85	25.0	1.29	--	--	--	--	--	--

Specimen #2

	1t slope	1t conc	3t slope	3t conc	5t slope	5t conc	7t slope	7t conc	9t slope	9t conc	11t slope	11t conc
1	13.8	0.77	14.0	0.78	13.9	0.78	13.5	0.75	13.2	0.74	14.1	0.79
2	19.4	1.08	19.4	1.08	19.5	1.09	20.3	1.13	20.1	1.12	19.4	1.08
3	8.4	0.47	8.9	0.50	9.1	0.51	9.0	0.50	8.6	0.48	9.0	0.50
4	16.4	0.92	16.8	0.94	16.6	0.93	15.9	0.89	15.9	0.89	15.4	0.86
5	18.4	1.03	18.5	1.03	19.2	1.07	19.2	1.07	19.7	1.10	18.6	1.04
6	8.4	0.47	8.6	0.48	9.4	0.52	9.6	0.54	9.2	0.51	10.2	0.57
7	- 8.1	-0.45	- 7.8	-0.44	- 8.1	-0.45	- 7.4	-0.41	- 7.2	-0.40	- 6.9	-0.39
8	6.7	0.37	7.2	0.40	8.0	0.45	8.7	0.49	9.0	0.50	9.3	0.52
9	- 7.2	-0.40	- 7.0	-0.39	- 5.0	-0.28	- 3.9	-0.22	- 3.5	-0.20	- 3.1	-0.17
10	21.0	1.17	20.5	1.14	20.9	1.17	20.3	1.13	20.3	1.13	20.0	1.12
11	--	--	--	--	--	--	--	--	--	--	--	--
12	25.0	1.40	24.7	1.38	23.3	1.30	22.1	1.23	22.3	1.24	22.1	1.23
13	- 5.0	-0.28	- 5.1	-0.28	- 5.6	-0.31	- 6.0	-0.33	- 5.9	-0.33	- 5.5	-0.31
14	21.6	1.21	20.6	1.15	20.2	1.13	20.3	1.13	20.4	1.14	20.1	1.12
15	- 3.8	-0.21	- 3.9	-0.22	- 4.5	-0.25	- 4.5	-0.25	- 4.7	-0.26	- 5.0	-0.28
16	19.4	1.08	20.0	1.12	19.8	1.10	20.1	1.12	19.7	1.10	19.7	1.10
17	- 4.2	-0.23	- 4.9	-0.27	- 5.1	-0.28	- 4.2	-0.23	- 4.7	-0.26	- 4.5	-0.25
18	13.7	0.76	13.4	0.75	13.6	0.76	13.4	0.75	13.6	0.76	13.8	0.77
19	4.8	0.27	5.8	0.32	6.8	0.38	7.5	0.42	8.0	0.45	9.2	0.51
20	-13.0	-0.73	- 9.9	-0.55	- 6.3	-0.35	- 4.6	-0.26	- 3.7	-0.21	- 2.7	-0.15
21	30.0	1.67	35.0	1.95	37.9	2.11	38.0	2.12	40.0	2.23	41.0	2.29
22	3.0	0.17	4.2	0.23	5.3	0.30	5.4	0.30	6.6	0.37	7.0	0.39
23	-10.5	-0.59	-15.3	-0.85	-16.7	-0.93	-16.6	-0.93	-18.3	-1.02	-20.8	-1.16
24	28.4	1.58	28.0	1.56	24.7	1.38	21.7	1.21	18.7	1.04	18.2	1.02
25	- 8.7	-0.49	-10.5	-0.59	-11.6	-0.65	-11.8	-0.66	-12.2	-0.68	-11.9	-0.66
26	-10.2	-0.57	- 7.4	-0.41	- 5.8	-0.32	- 5.5	-0.31	- 4.6	-0.26	- 3.8	-0.21
27	- 5.1	-0.28	- 4.3	-0.24	- 3.5	-0.20	- 3.4	-0.19	- 3.4	-0.19	- 2.7	-0.15
28	4.7	0.26	4.1	0.23	3.8	0.21	3.4	0.19	4.1	0.23	4.5	0.25
29	42.0	2.34	35.2	1.96	33.5	1.87	32.8	1.83	32.6	1.82	31.9	1.78
30	51.9	2.90	44.7	2.49	31.7	1.77	35.4	1.98	35.8	2.00	34.4	1.92
31	45.0	2.51	37.6	2.10	34.2	1.91	32.1	1.79	31.9	1.78	30.8	1.72
32	2[illegible].9	1.57	24.7	1.38	20.7	1.16	18.3	1.02	15.3	0.85	14.5	0.81
33	28.3	1.58	26.2	1.46	23.3	1.30	20.0	1.12	17.7	0.99	15.6	0.87
34	--	--	-12.8	-0.71	- 8.6	-0.48	- 6.0	-0.33	- 4.4	-0.25	- 4.4	-0.25
35	--	--	- 3.3	-0.18	- 1.6	-0.09	0.0	0.00	1.0	0.06	2.2	0.12
36	--	--	5.9	0.33	3.3	0.18	2.0	0.11	0.0	0.00	0.5	0.03
37	--	--	29.5	1.65	24.1	1.34	20.6	1.15	19.4	1.08	19.7	1.10
38	--	--	29.5	1.65	24.7	1.38	20.7	1.16	18.7	1.04	16.5	0.92

Specimen #3

	1t slope	1t conc	3t slope	3t conc	5t slope	5t conc	7t slope	7t conc	9t slope	9t conc	11t slope	11t conc
1	15.3	0.85	14.9	0.83	14.8	0.82	15.0	0.83	15.1	0.84	15.5	0.86
2	20.5	1.14	20.8	1.16	21.5	1.19	21.2	1.18	21.0	1.17	21.1	1.17
3	7.5	0.42	6.5	0.36	5.5	0.31	7.5	0.42	7.5	0.42	7.6	0.42
4	-10.6	-0.59	-10.5	-0.58	-10.4	-0.58	-10.5	-0.58	-10.3	-0.57	-10.4	-0.58
5	14.1	0.78	13.4	0.74	13.7	0.76	13.3	0.74	13.9	0.77	14.0	0.78
6	20.9	1.16	21.3	1.18	20.7	1.15	20.8	1.16	20.7	1.15	20.9	1.16
7	--	--	--	--	--	--	--	--	--	--	--	--
8	7.0	0.39	7.4	0.41	7.9	0.44	8.6	0.48	9.4	0.52	9.0	0.50
9	-10.2	-0.57	-11.0	-0.61	-10.7	-0.59	-11.1	-0.62	-10.6	-0.59	-10.9	-0.61
10	6.0	0.33	7.6	0.42	8.5	0.47	9.2	0.51	9.7	0.54	9.7	0.54
11	--	--	--	--	--	--	--	--	---	--	--	--
12	- 9.4	-0.52	- 8.9	-0.49	- 6.8	-0.38	- 5.0	-0.28	- 5.2	-0.29	- 5.0	-0.28
13	20.5	1.14	21.1	1.17	21.6	1.20	20.9	1.16	21.2	1.18	21.3	1.18
14	25.0	1.39	23.8	1.32	23.7	1.32	23.1	1.28	22.3	1.24	22.0	1.22
15	- 5.0	-0.28	- 5.4	-0.30	- 5.6	-0.31	- 5.9	-0.33	- 5.8	-0.32	- 5.6	-0.31
16	20.3	1.13	21.0	1.17	21.2	1.18	21.1	1.17	21.0	1.17	20.6	1.15
17	- 3.9	-0.32	- 3.8	-0.21	- 4.0	-0.22	- 4.4	-0.24	- 4.1	-0.23	- 3.9	-0.22
18	19.7	1.10	20.4	1.13	20.6	1.15	21.1	1.17	21.2	1.18	21.0	1.17
19	- 4.6	-0.26	- 4.5	-0.25	- 4.5	-0.25	- 4.5	-0.25	- 4.4	-0.24	- 4.5	-0.25
20	15.0	0.83	14.3	0.80	13.9	0.77	13.8	0.77	13.9	0.77	13.8	0.77
21	5.0	0.28	6.3	0.35	8.0	0.44	8.9	0.49	9.5	0.53	10.1	0.56
22	-12.7	-0.71	-10.0	-0.56	- 5.6	-0.31	- 3.6	-0.20	- 2.7	-0.15	- 2.0	-0.11
23	29.1	1.62	33.4	1.86	35.0	1.95	38.8	2.16	37.8	2.10	36.4	2.02
24	3.0	0.17	4.9	0.27	6.2	0.34	6.5	0.36	7.0	0.39	7.0	0.39
25	- 8.0	-0.44	-16.1	-0.90	-17.5	-0.97	-19.3	-1.07	-19.2	-1.07	-19.3	-1.07
26	30.9	1.72	30.1	1.67	25.7	1.43	23.6	1.31	21.1	1.17	20.3	1.13
27	- 8.4	-0.47	- 8.9	-0.49	-11.3	-0.63	-10.3	-0.57	-10.4	-0.58.	-10.9	-0.61
28	-12.9	-0.72	- 9.0	-0.50	- 7.1	-0.39	- 5.4	-0.30	- 5.1	-0.28	- 5.5	-0.31
29	--	--	- 7.2	-0.40	- 5.3	-0.29	- 5.2	-0.29	- 5.0	-0.28	- 5.0	-0.28
30	-11.2	-0.62	- 5.7	-0.32	- 5.0	-0.28	- 4.0	-0.22	- 3.9	-0.22	- 3.8	-0.21
31	3.1	0.17	5.1	0.28	6.5	0.36	5.7	0.32	5.4	0.30	5.0	0.28
32	38.6	2.15	26.5	1.47	25.0	1.39	23.9	1.33	24.2	1.35	24.1	1.34
33	54.8	3.05	36.8	2.05	34.1	1.90	37.3	2.07	35.2	1.96	34.9	1.94
34	41.1	2.29	40.3	2.24	36.5	2.03	35.5	1.97	33.7	1.87	34.5	1.92
35	32.2	1.79	27.4	1.52	23.3	1.30	20.5	1.14	17.5	0.97	15.5	0.86
36	--	--	34.3	1.91	28.5	1.58	23.6	1.31	23.3	1.30	18.1	1.01
37	--	--	-12.8	-0.71	- 7.5	-0.42	- 4.1	-0.23	- 3.1	-0.17	- 2.2	-0.12
38	--	--	- 5.0	-0.28	0.0	0.00	0.3	0.02	2.0	0.11	2.7	0.15
39	--	--	12.6	0.70	10.1	0.56	8.6	0.48	8.4	0.47	6.7	0.37
40	--	--	29.6	1.65	23.8	1.32	20.3	1.13	18.8	1.05	17.4	0.97
41	--	--	34.2	1.90	29.0	1.61	24.0	1.33	21.3	1.18	19.6	1.09

Specimen #4

	1t slope	1t conc	3t slope	3t conc	5t slope	5t conc	7t slope	7t conc	9t slope	9t conc	11t slope	11t conc
1	18.9	0.97	19.9	1.02	18.1	0.92	18.6	0.95	19.0	0.97	19.3	0.97
2	18.9	0.97	19.4	0.99	18.7	0.96	18.4	0.94	19.2	0.98	20.7	1.06
3	15.0	0.77	15.2	0.78	15.7	0.80	15.6	0.80	16.0	0.82	15.0	0.77
4	--	--	3.3	0.17	3.5	0.18	4.2	0.21	5.0	0.26	5.0	0.26
5	--	--	29.0	1.48	25.0	1.28	22.6	1.15	21.0	1.07	18.1	0.92
6	--	--	- 5.3	-0.27	- 5.2	-0.27	- 6.9	-0.35	- 6.0	-0.31	- 7.2	-0.37
7	--	--	- 4.8	-0.25	- 4.4	-0.22	- 4.1	-0.21	- 3.3	-0.17	- 5.0	-0.26
8	21.9	1.12	20.0	1.02	21.3	1.09	20.5	1.05	24.2	1.24	22.5	1.15
9	--	--	- 5.1	-0.26	- 3.8	-0.19	- 3.1	-0.16	- 2.6	-0.13	- 3.2	-0.16
10	--	--	- 1.9	-0.10	- 1.2	-0.06	- 1.0	-0.05	- 3.0	-0.15	0.0	0.00
11	16.2	0.83	16.1	0.82	16.9	0.86	17.0	0.87	19.0	0.97	17.2	0.88
12	7.5	0.38	9.7	0.50	10.1	0.52	10.9	0.57	11.0	0.56	11.4	0.58
13	20.0	1.02	19.3	0.99	19.2	0.98	21.1	1.08	22.2	1.13	22.5	1.15
14	--	--	6.4	0.33	5.8	0.30	7.1	0.36	7.2	0.37	6.2	0.32
15	--	--	8.8	0.45	8.2	0.42	6.9	0.35	6.7	0.34	6.4	0.33
16	1.5	0.08	2.9	0.15	3.0	0.15	3.5	0.18	3.2	0.16	0.0	0.00
17	- 7.3	-0.37	- 7.3	-0.37	- 7.1	-0.36	- 7.9	-0.40	- 9.3	-0.48	-11.4	-0.58
18	- 3.4	-0.17	- 3.3	-0.17	- 3.9	-0.20	- 3.9	-0.20	- 4.3	-0.22	- 5.0	-0.26
19	-10.3	-0.53	-11.0	-0.56	-12.3	-0.63	-14.3	-0.73	-16.2	-0.83	-18.1	-0.92
20	--	--	15.0	0.77	13.5	0.69	12.8	0.65	12.1	0.62	12.2	0.62
21	9.3	0.48	9.0	0.46	8.1	0.41	8.1	0.41	9.3	0.48	8.6	0.44
22	- 5.2	-0.27	- 5.1	-0.26	- 5.1	-0.26	- 5.4	-0.28	- 6.4	-0.33	- 8.6	-0.44
23	[illegible]	1.30	28.4	1.45	29.2	1.49	30.8	1.57	31.8	1.62	33.1	1.69
24	31.0	1.58	25.9	1.32	23.0	1.18	21.4	1.09	20.0	1.02	18.1	0.92
25	--	--	15.6	0.80	16.5	0.84	16.4	0.84	16.0	0.82	15.7	0.80
26	22.0	1.12	19.6	1.00	20.8	1.06	20.4	1.04	21.7	1.11	22.9	1.17
27	18.1	0.92	17.5	0.89	18.4	0.94	19.5	1.00	20.7	1.06	21.4	1.09
28	20.2	1.03	19.0	0.97	19.7	1.01	19.9	1.02	20.3	1.04	20.7	1.06
29	- 8.6	-0.44	- 7.1	-0.36	- 7.4	-0.38	- 8.3	-0.42	--	--	--	--
30	- 3.4	-0.17	- 1.5	-0.08	- 1.8	-0.09	- 1.6	-0.08	- 2.2	-0.11	0.0	0.00
31	14.9	0.76	15.0	0.77	15.2	0.78	15.5	0.79	15.0	0.77	14.3	0.73
32	20.9	1.07	21.0	1.07	20.4	1.04	20.1	1.03	19.3	0.99	17.9	0.91
33	- 2.9	-0.15	- 3.1	-0.16	- 3.4	-0.17	- 3.3	-0.17	- 4.6	-0.24	- 5.7	-0.29
34	--	--	- 6.1	-0.31	- 4.3	-0.22	- 3.7	-0.19	- 3.6	-0.18	- 3.8	-0.19
35	15.7	0.80	14.8	0.76	15.3	0.78	15.0	0.77	15.7	0.80	16.4	0.84
36	16.9	0.86	16.4	0.84	17.3	0.88	18.1	0.92	19.0	0.97	17.9	0.91
37	- 2.0	-0.10	- 1.8	-0.09	- 2.2	-0.11	- 2.5	-0.13	- 3.7	-0.19	- 3.6	-0.18
38	- 2.8	-0.14	- 2.8	-0.14	- 3.0	-0.15	- 3.6	-0.18	- 4.3	-0.22	- 4.3	-0.22
39	- 8.5	-0.43	- 7.0	-0.36	- 6.6	-0.34	- 6.5	-0.33	- 8.2	-0.42	- 9.4	-0.48
40	--	--	- 6.8	-0.35	- 4.9	-0.25	- 4.1	-0.21	- 3.3	-0.16	- 4.3	-0.22
41	22.3	1.14	20.6	1.05	20.3	1.04	20.6	1.05	21.7	1.11	22.9	1.17
42	--	--	--	--	--	--	20.0	1.02	21.5	1.10	22.9	1.17
43	--	--	14.4	0.74	14.3	0.73	14.7	0.75	15.0	0.77	13.6	0.69
44	--	--	26.7	1.36	23.8	1.22	21.4	1.09	21.0	1.07	18.9	0.97
45	--	--	- 8.4	-0.43	- 7.3	-0.37	- 7.0	-0.36	- 6.4	-0.33	- 9.3	-0.48

Continued on next page.

Specimen #4 (Continued)

	1t slope	1t conc	3t slope	3t conc	5t slope	5t conc	7t slope	7t conc	9t slope	9t conc	11t slope	11t conc
46	- 7.2	-0.37	- 7.3	-0.37	- 7.0	-0.36	- 7.0	-0.36	- 9.0	-0.46	- 9.3	-0.48
47	- 4.2	-0.21	- 4.0	-0.20	- 4.1	-0.21	- 4.0	-0.20	- 4.0	-0.20	- 4.3	-0.22
48	19.3	0.99	17.4	0.89	18.5	0.95	19.0	0.97	19.6	1.00	20.0	1.02
49	--	---	28.4	1.45	24.0	1.23	21.9	1.12	18.7	0.96	16.9	0.86
50	--	--	--	--	--	--	--	--	- 6.4	-0.33	- 5.7	-0.29
51	-14.7	-0.75	- 9.0	-0.46	- 7.3	-0.37	- 8.0	-0.41	- 5.7	-0.29	- 7.9	-0.40
52	--	--	26.3	1.34	21.2	1.08	20.5	1.05	20.0	1.02	16.4	0.84
53	--	--	- 9.9	-0.51	- 8.0	-0.41	- 7.7	-0.39	- 7.1	-0.36	- 7.9	-0.40
54	--	--	---	--	--	--	20.3	1.04	18.6	0.95	17.2	0.88
55	31.9	1.63	28.1	1.44	23.9	1.22	20.0	1.02	17.2	0.88	12.9	0.66
56	50.8	2.60	43.8	2.24	37.5	1.92	35.7	1.82	35.7	1.82	44.3	2.26
57	--	--	--	--	--	--	--	--	- 7.2	-0.37	- 7.9	-0.40
58	--	--	--	--	--	--	--	--	- 3.7	-0.19	- 3.6	-0.18
59	--	--	--	--	--	--	--	--	15.7	0.80	15.0	0.77
60	--	--	--	--	--	--	--	--	13.6	0.69	14.3	0.73

Specimen #5

	1t slope	1t conc	3t slope	3t conc	5t slope	5t conc	7t slope	7t conc	9t slope	9t conc	11t slope	11t conc
1	17.1	0.88	16.7	0.86	16.3	0.84	16.1	0.83	15.9	0.82	15.9	0.82
2	20.8	1.07	20.7	1.06	21.2	1.09	20.4	1.05	21.0	1.08	21.6	1.11
3	16.0	0.82	15.7	0.81	15.5	0.80	15.2	0.78	15.1	0.78	17.9	0.92
4	11.5	0.59	11.7	0.60	11.8	0.61	11.7	0.60	11.8	0.61	11.9	0.61
5	- 2.4	-0.12	- 2.2	-0.11	- 2.1	-0.11	- 2.3	-0.12	- 2.4	-0.12	- 2.5	-0.13
6	21.5	1.10	21.8	1.12	21.2	1.09	21.2	1.09	22.0	1.13	21.7	1.11
7	15.0	0.77	14.8	0.76	14.7	0.75	14.6	0.75	13.9	0.71	14.6	0.75
8	--	--	--	--	--	--	--	--	--	--	14.9	0.77
9	15.5	0.80	16.5	0.85	16.9	0.87	17.5	0.90	17.3	0.89	16.9	0.87
10	- 1.7	-0.09	- 1.8	-0.09	- 1.8	-0.09	- 2.2	-0.11	- 2.1	-0.11	- 1.8	-0.09
11	8.3	0.43	10.4	0.53	11.0	0.56	11.8	0.60	11.9	0.61	12.0	0.62
12	- 0.9	-0.05	0.0	0.00	- 0.5	-0.03	- 0.5	-0.03	- 0.6	-0.03	- 0.5	-0.03
13	20.0	1.03	19.1	0.98	18.3	0.94	18.0	0.92	17.4	0.89	16.6	0.85
14	20.9	1.07	19.9	1.02	19.6	1.00	19.8	1.02	19.0	0.97	18.2	0.93
15	- 6.9	-0.35	- 6.1	-0.31	- 5.3	-0.27	- 5.1	-0.26	- 4.9	-0.25	- 5.0	-0.26
16	--	--	--	--	16.0	0.82	15.6	0.80	15.9	0.82	16.5	0.85
17	- 1.7	-0.09	- 1.8	-0.09	- 1.8	-0.09	- 1.5	-0.08	- 1.4	-0.07	- 1.3	-0.07
18	17.3	0.89	15.9	0.82	15.0	0.77	14.9	0.76	14.4	0.74	13.8	0.71
19	- 3.5	-0.18	- 3.9	-0.20	- 3.8	-0.19	- 4.0	-0.21	- 3.8	-0.19	- 3.9	-0.20
20	16.8	0.86	14.9	0.76	14.3	0.73	14.5	0.74	15.0	0.77	15.0	0.77
21	- 4.1	-0.21	- 4.5	-0.23	- 4.0	-0.20	- 4.5	-0.23	- 4.5	-0.23	- 4.1	-0.21
22	1.0	0.05	1.5	0.08	0.7	0.04	0.5	0.03	0.0	0.00	0.0	0.00
23	- 8.1	-0.42	- 2.9	-0.15	- 1.5	-0.08	- 1.0	-0.05	- 0.7	-0.04	0.0	0.00
24	20.7	1.06	20.9	1.07	21.0	1.08	20.5	1.05	21.2	1.09	21.3	1.09
25	0.0	0.00	1.6	0.08	2.4	0.12	2.5	0.13	3.0	0.15	4.5	0.23
26	- 7.8	-0.40	- 7.5	-0.38	- 7.5	-0.38	- 6.2	-0.32	- 6.8	-0.35	- 6.4	-0.33
27	--	--	10.9	0.56	10.5	0.54	9.8	0.50	9.4	0.48	9.2	0.47
28	- 5.0	-0.26	- 4.3	-0.22	- 2.3	-0.12	- 2.0	-0.10	- 2.0	-0.10	--	--
29	16.1	0.83	16.2	0.83	16.2	0.83	16.1	0.83	15.6	0.80	15.4	0.79
30	--	--	33.8	1.73	30.0	1.54	27.0	1.39	25.0	1.28	12.5	0.64
31	-15.8	-0.81	-10.4	-0.53	- 7.4	-0.38	- 6.6	-0.34	- 6.5	-0.33	- 5.1	-0.26
32	-16.9	-0.87	-10.6	-0.54	- 8.4	-0.43	- 7.1	-0.36	- 6.5	-0.33	- 7.4	-0.38
33	--	--	17.2	0.88	15.3	0.78	15.0	0.77	15.0	0.77	15.0	0.77
34	--	--	34.8	1.79	31.0	1.59	29.6	1.52	29.0	1.49	29.3	1.50
35	37.4	1.92	35.0	1.80	30.3	1.55	27.2	1.40	25.8	1.32	25.0	1.28
36	--	--	28.2	1.45	23.1	1.19	19.7	1.01	18.2	0.93	17.6	0.90
37	--	--	- 5.0	-0.26	- 2.8	-0.14	- 2.0	-0.10	- 1.8	-0.09	- 1.6	-0.08
38	30.5	1.56	27.5	1.41	24.3	1.25	22.4	1.15	21.4	1.10	21.0	1.08
39	--	--	26.3	1.35	22.7	1.16	20.5	1.05	19.3	0.99	19.1	0.98
40	--	--	24.2	1.24	21.5	1.10	19.0	0.97	17.3	0.89	16.7	0.86
41	--	--	--	--	--	--	--	--	- 2.9	-0.15	- 2.7	-0.14
42	--	--	--	--	--	--	--	--	- 6.7	-0.34	- 5.0	-0.26
43	--	--	--	--	--	--	--	--	12.9	0.66	10.0	0.51
9B	10.6	0.54	11.4	0.58	11.5	0.59	--	---	--	--	--	--
24B	21.4	1.10	23.9	1.23	23.1	1.19	--	--	--	--	--	--
38B	--	--	23.3	1.20	18.5	0.95	--	--	--	--	--	--

Specimen #6

	1t slope	1t conc	3t slope	3t conc	5t slope	5t conc	7t slope	7t conc	9t slope	9t conc	11t slope	11t conc
1	18.7	0.95	18.0	0.92	18.2	0.93	17.7	0.90	18.4	0.94	17.8	0.91
2	18.7	0.95	19.2	0.98	19.2	0.98	20.0	1.02	20.1	1.02	19.0	0.97
3	--	--	--	--	--	--	--	--	--	--	--	--
4	- 4.5	-0.23	- 5.5	-0.28	- 6.9	-0.35	- 7.5	-0.38	- 7.4	-0.38	- 6.8	-0.35
5	18.9	0.96	18.4	0.94	17.7	0.90	17.6	0.90	17.4	0.89	18.0	0.92
6	18.6	0.9	19.3	0.98	19.8	1.01	19.8	1.01	20.0	1.02	19.5	0.99
7	20.5	1.04	20.8	1.06	20.0	1.02	19.6	1.00	19.2	0.98	19.9	1.01
8	12.5	0.64	12.3	0.63	12.5	0.64	12.6	0.64	12.8	0.65	12.9	0.65
9	- 4.6	-0.23	- 6.5	-0.33	- 7.0	-0.36	- 5.8	-0.30	- 5.6	-0.29	- 5.6	-0.29
10	8.5	0.43	9.8	0.50	11.0	0.56	11.0	0.56	11.8	0.60	11.8	0.60
11	- 4.4	-0.22	- 5.0	-0.25	- 5.3	-0.27	- 5.5	-0.28	- 5.0	-0.25	- 4.9	-0.25
12	21.9	1.11	21.3	1.08	21.3	1.08	22.2	1.13	21.9	1.11	22.1	1.12
13	20.3	1.03	19.5	0.99	19.0	0.97	19.4	0.99	19.0	0.97	19.7	1.00
14	- 7.8	- 0.40	- 8.5	-0.43	- 8.3	-0.42	- 8.5	-0.43	- 8.0	-0.41	- 8.4	-0.43
15	21.2	1.08	21.1	1.07	21.0	1.07	20.4	1.04	20.0	1.02	20.3	1.03
16	--	--	- 9.4	-0.48	- 6.2	-0.32	- 4.3	-0.22	- 4.2	-0.21	- 4.1	-0.21
17	20.1	1.02	21.1	1.07	21.6	1.10	21.4	1.09	21.2	1.08	20.7	1.05
18	--	--	--	--	--	--	--	--	--	--	--	--
19	19.5	0.99	20.1	1.02	20.6	1.05	21.0	1.07	20.6	1.05	19.9	1.01
20	--	--	--	--	--	--	--	--	--	--	--	--
21	15.1	0.77	15.5	0.79	15.2	0.77	14.8	0.75	14.8	0.75	15.1	0.77
22	34.5	1.76	27.3	1.39	24.2	1.23	21.3	1.08	20.9	1.06	20.5	1.04
23	--	--	29.3	1.49	23.6	1.20	21.4	1.09	20.0	1.02	20.0	1.02
24	23.5	1.20	24.8	1.26	25.7	1.31	26.1	1.33	26.2	1.33	2[illegible].3	1.29
25	0.0	0.00	1.9	0.10	2.6	0.13	2.7	0.14	3.1	0.16	2.6	0.13
26	-10.9	-0.55	-12.3	-0.63	-13.5	-0.69	-14.3	-0.73	-13.9	-0.71	-13.5	-0.69
27	32.3	1.64	27.0	1.37	22.8	1.16	20.7	1.05	20.3	1.03	20.2	1.03
28	- 2.6	-0.13	- 2.0	-0.10	- 1.6	-0.08	- 1.7	-0.09	- 1.8	-0.09	- 1.8	-0.09
29	--	--	-11.4	-0.58	- 8.3	-0.42	- 6.7	-0.34	- 6.5	-0.33	- 6.4	-0.33
30	3.9	0.20	6.1	0.31	6.7	0.34	8.0	0.41	8.6	0.44	9.1	0.46
31	--	--	--	--	--	--	--	--	--	--	--	--
32	--	--	15.3	0.78	13.8	0.70	12.7	0.65	12.2	0.62	12.3	0.63
33	- 8.3	-0.42	- 5.2	-0.26	- 3.0	-0.15	- 1.3	-0.07	- 1.3	-0.07	- 0.6	-0.03
34	40.0	2.04	35.2	1.79	30.7	1.56	28.8	1.47	27.6	1.40	27.8	1.42
35	44.0	2.24	40.9	2.08	35.0	1.78	31.8	1.62	30.0	1.53	30.9	1.57
36	--	--	- 9.5	-0.48	- 4.2	-0.21	- 1.8	-0.09	- 1.1	-0.06	- 1.0	-0.05
37	--	--	12.2	0.62	10.5	0.53	10.0	0.51	9.1	0.46	9.7	0.49
38	--	--	--	--	--	--	--	--	17.9	0.91	16.1	0.82
39	--	--	--	--	--	--	--	--	14.3	0.73	10.4	0.53

Specimen #7

	slope	conc
1	18.8	0.94
2	19.8	0.99
3	20:2	1.01
4	20.0	1.00
5	18.6	0.93
6	19.6	0.98
7	20.0	1.00
8	19.3	0.97
9	18.1	0.91
10	20.0	1.00
11	19.1	0.95
12	20.0	1.00
13	18.7	0.94
14	19.9	1.00
15	20.0	1.00
16	20.0	1.00
17	18.6	0.93

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